Gravitational Wave Cosmology with Large Galaxy Surveys

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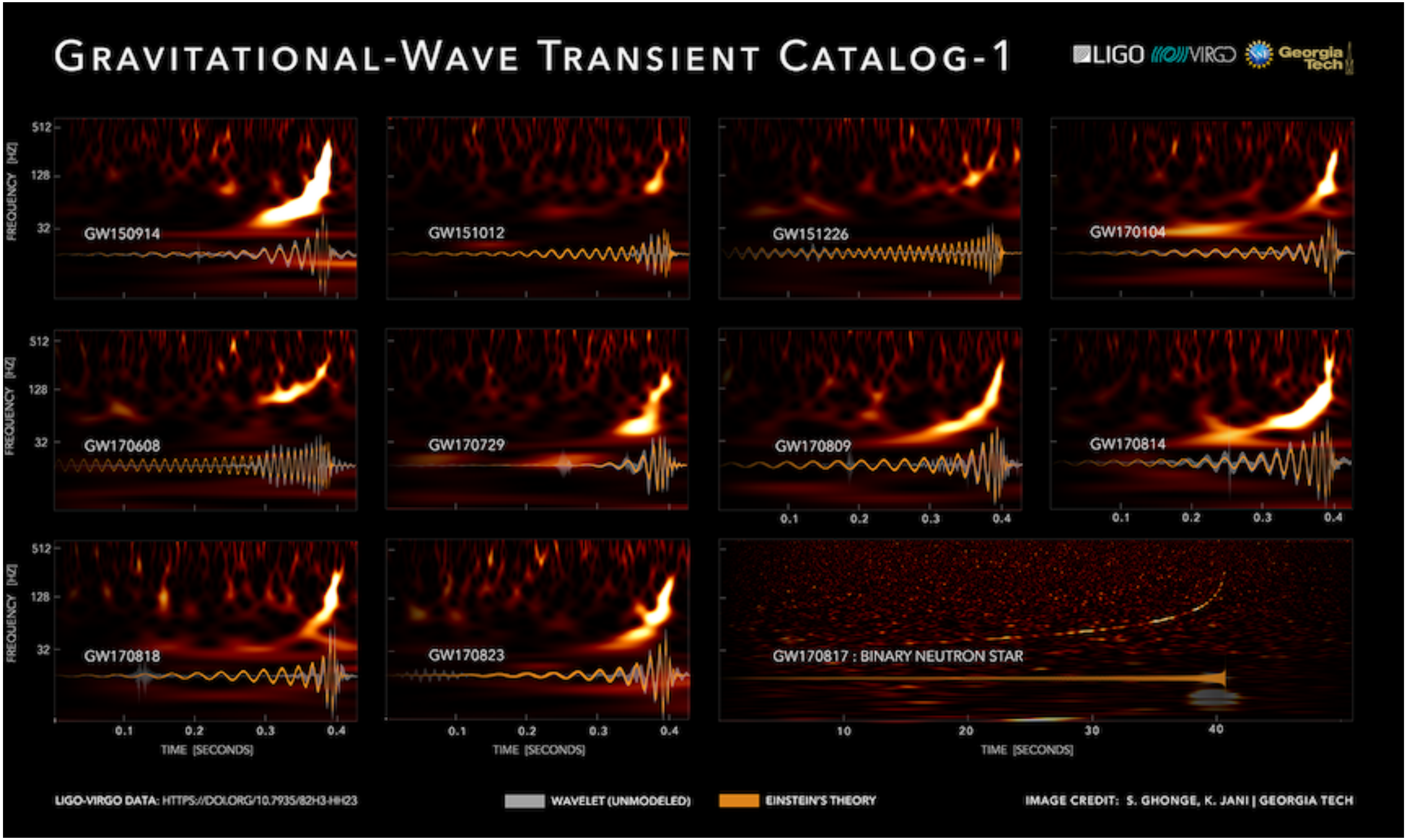
Published detections so far



O3 Candidates so far

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Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

Search

UID	Labels	t_start	t_0	t_end	FAR (Hz)	UTC Created
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S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
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LIGO VIRGO LSC

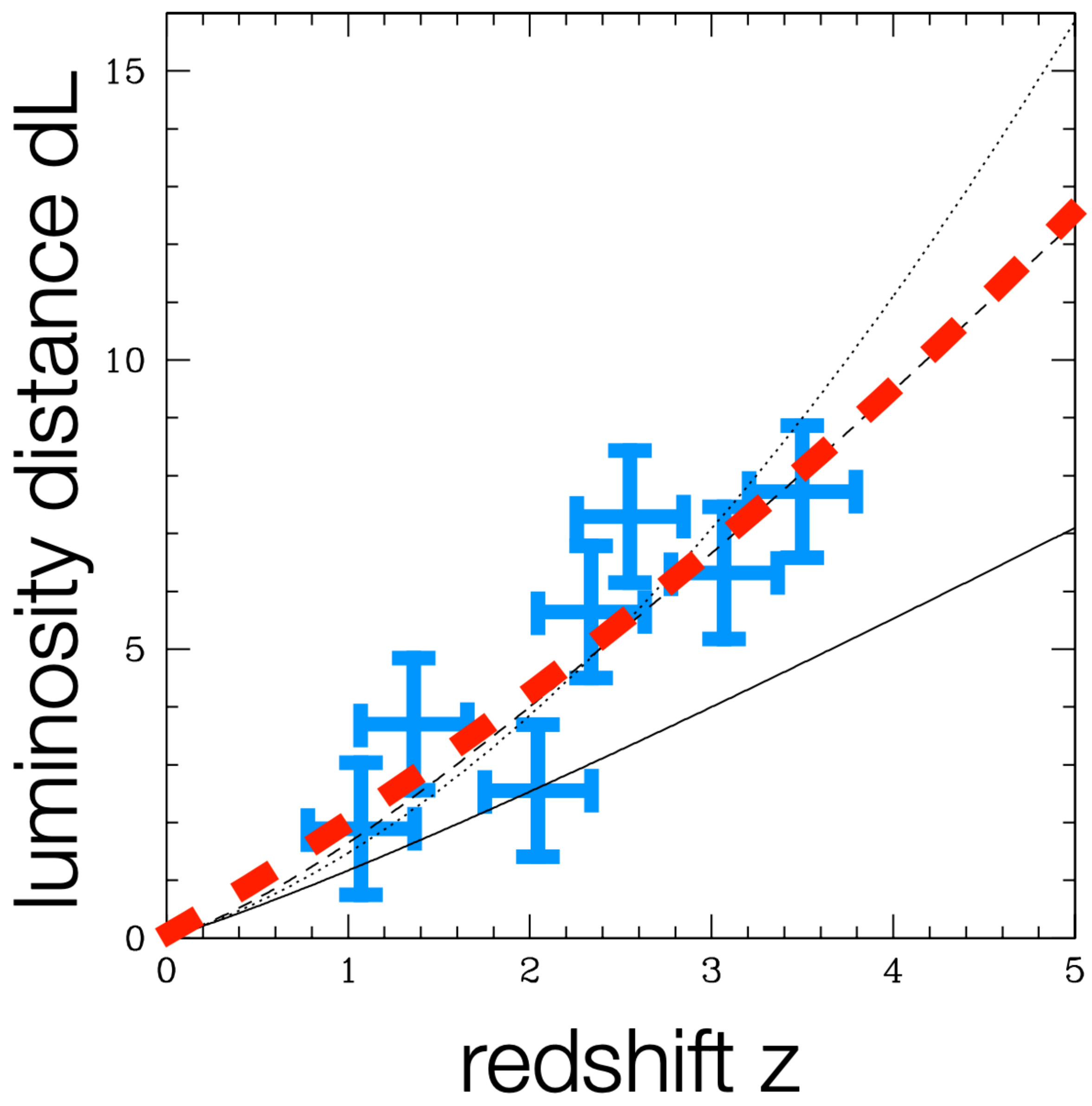
Review of Cosmology

- The relation between the luminosity distance and redshift is determined by some cosmological model and its parameters.

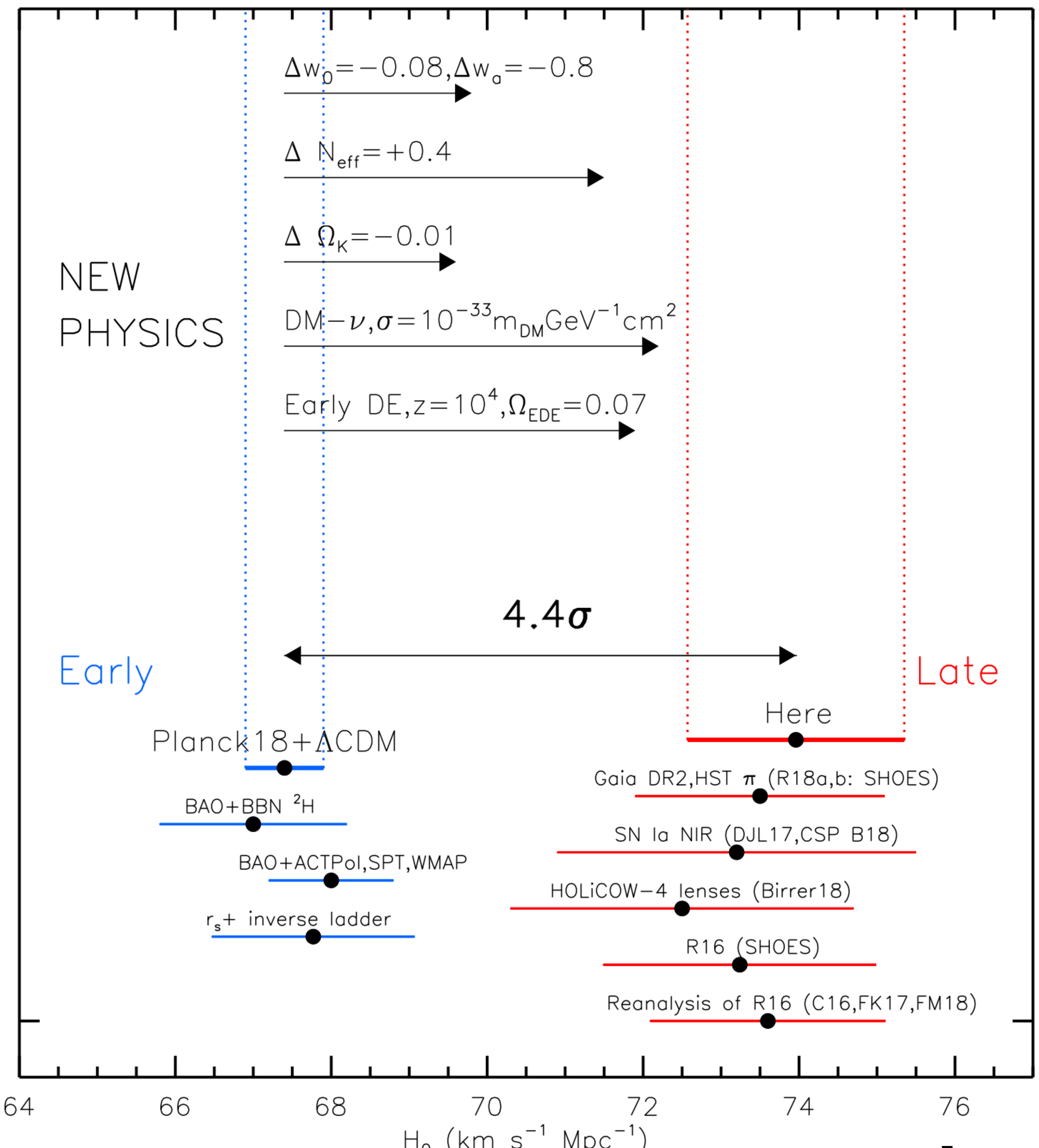
- Hence, getting measurements of both quantities allows us to compare models and constrain model parameters, e.g., the Hubble constant.

- In the local universe,

$$v_H = cz \approx H_0 d_L$$



Hubble constant tension



- Systematics?
    - Likely to be the case for the cosmic distance ladder due to calibration, astrophysics etc.
- Or new physics?
    - Evolving dark energy, non-zero curvature of the universe etc.

Distance, but not redshift

- Gravitational waves provide a direct measurement of luminosity distance, but they give no independent information about redshift, so called **"standard sirens"**.

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- Standard sirens are self-calibrating so long as GR is correct.

- GWs from a local binary with masses are indistinguishable from masses at redshift z.

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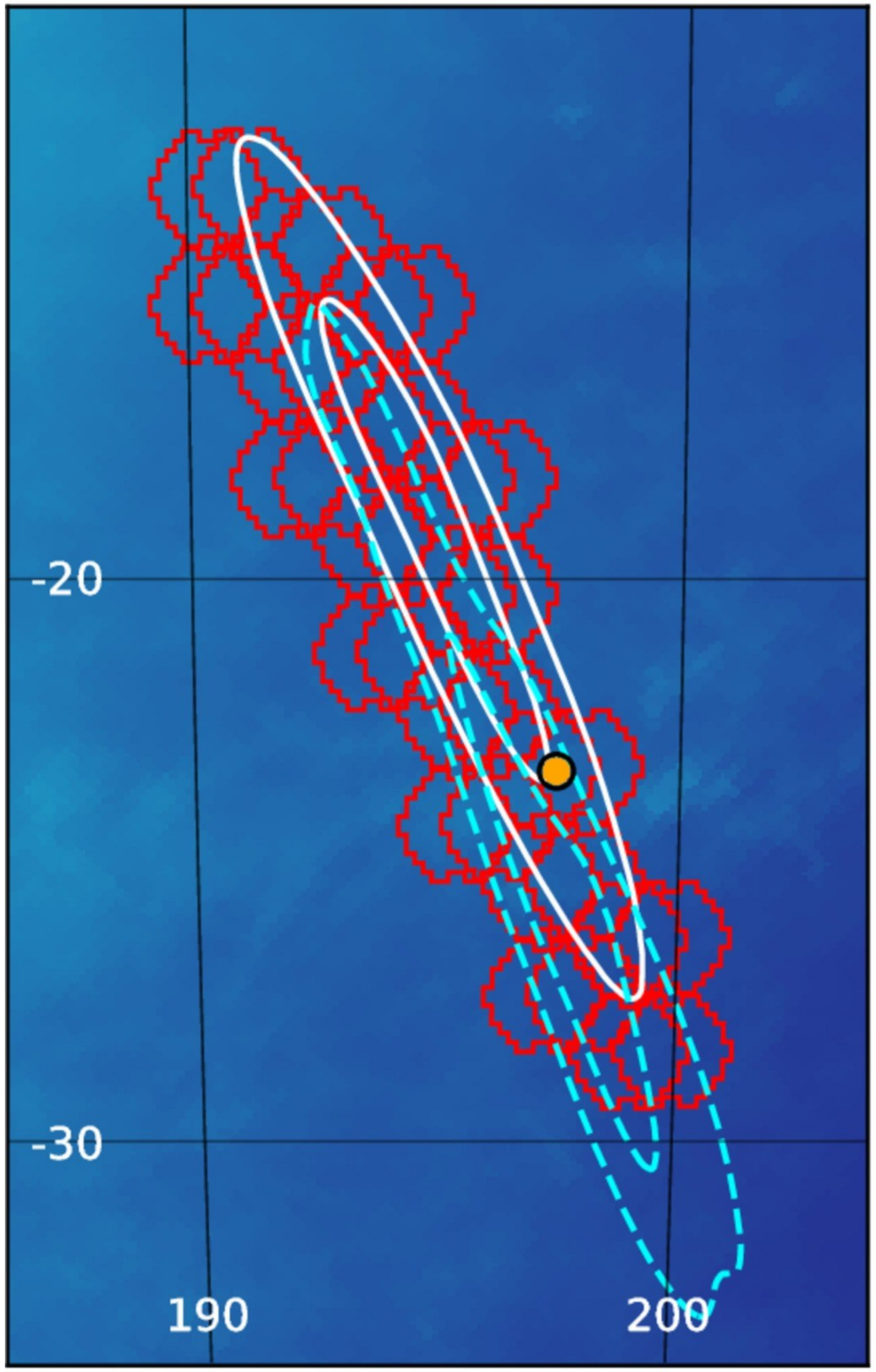
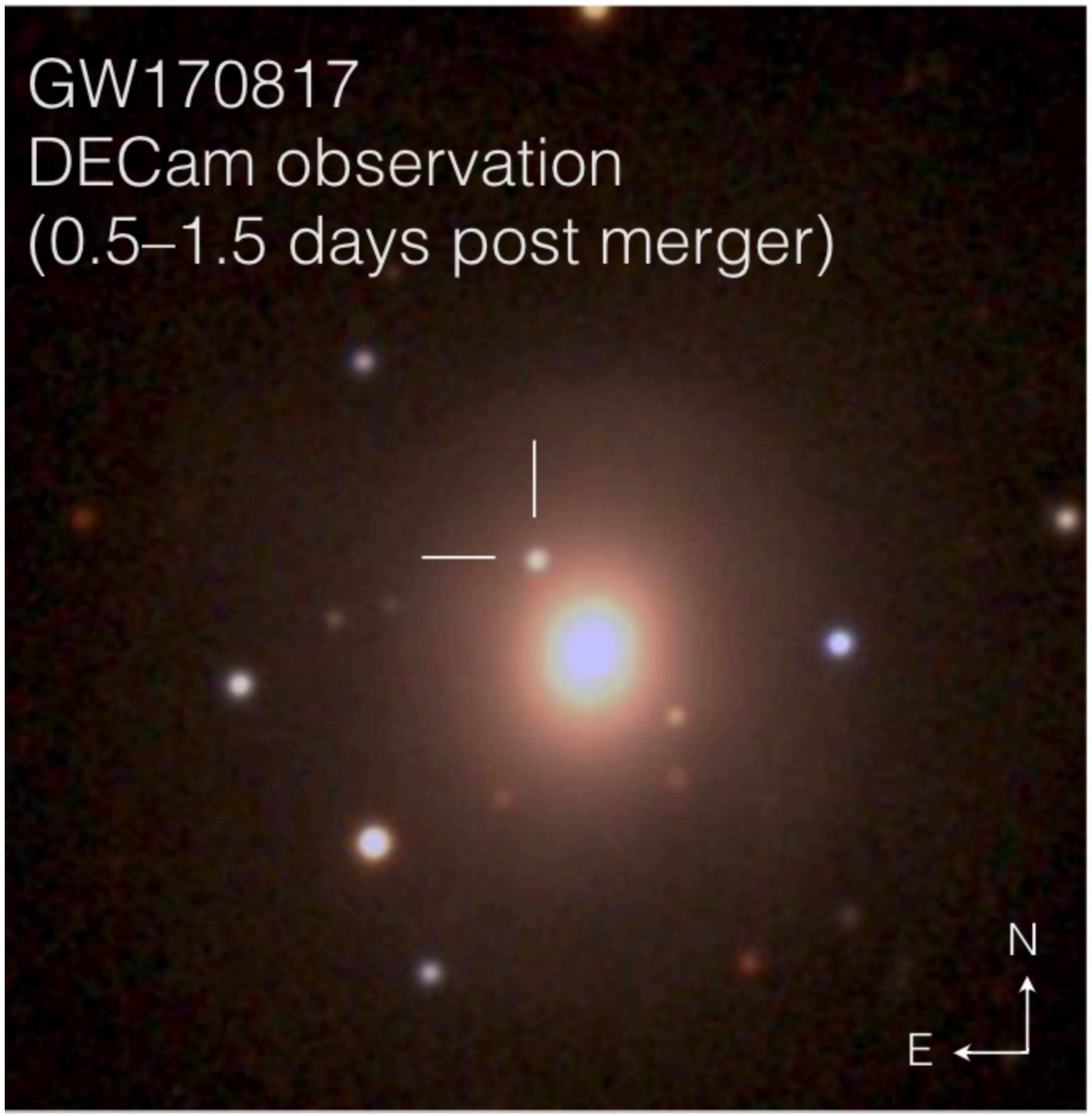
- If the post-merger signal is observed.
- Even if no EM counterpart found, one can use a reliable galaxy survey to cross correlate.

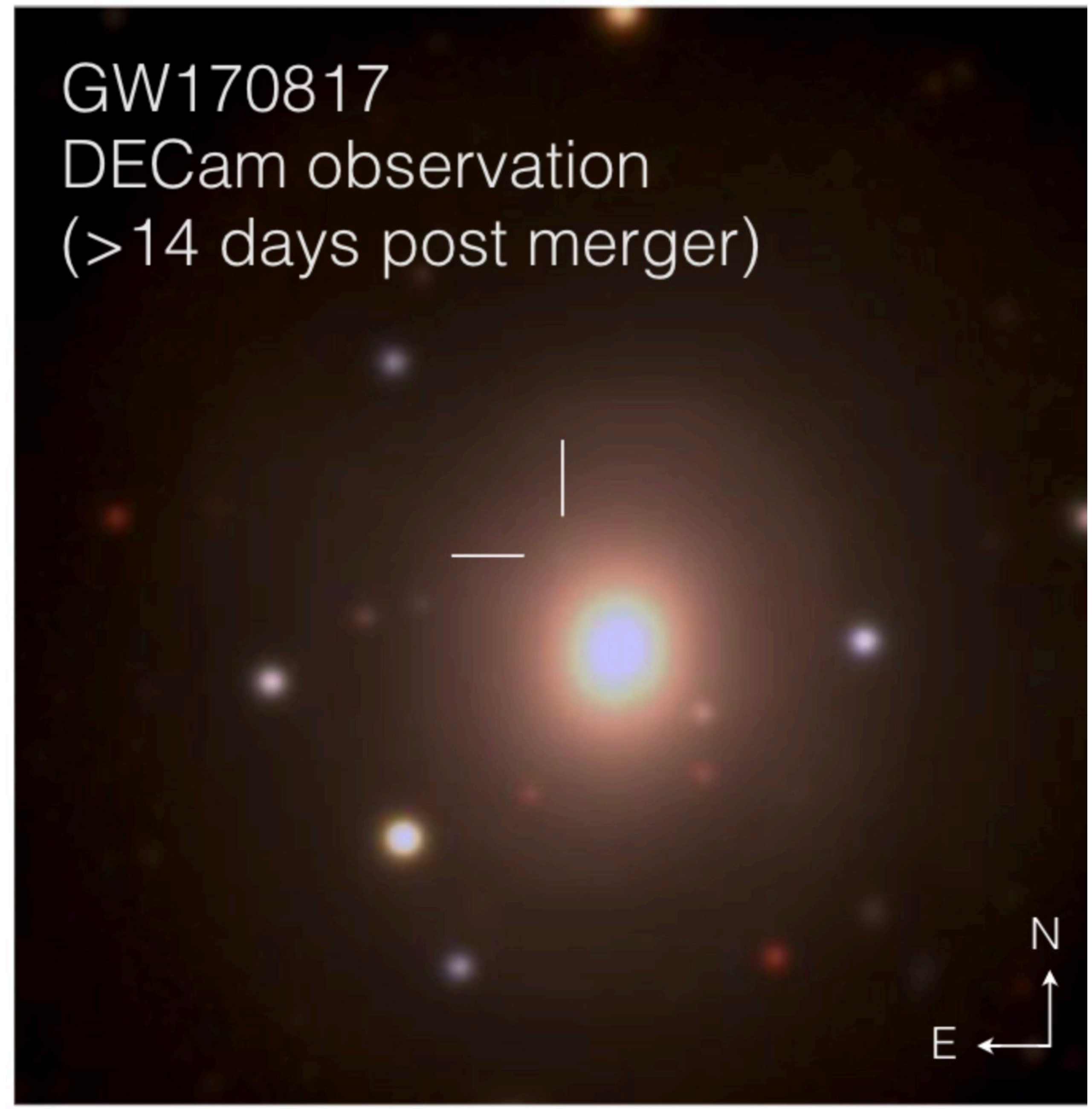
EM counterparts

- We now know that BNS merger can emit EM radiation over a wide range of frequencies.
- If the host galaxy is identified that can provide the redshift
- Challenges:
  - GW sky localization regions typically cover large portions of the sky.
  - Might be hard to follow up and find the associated counterpart

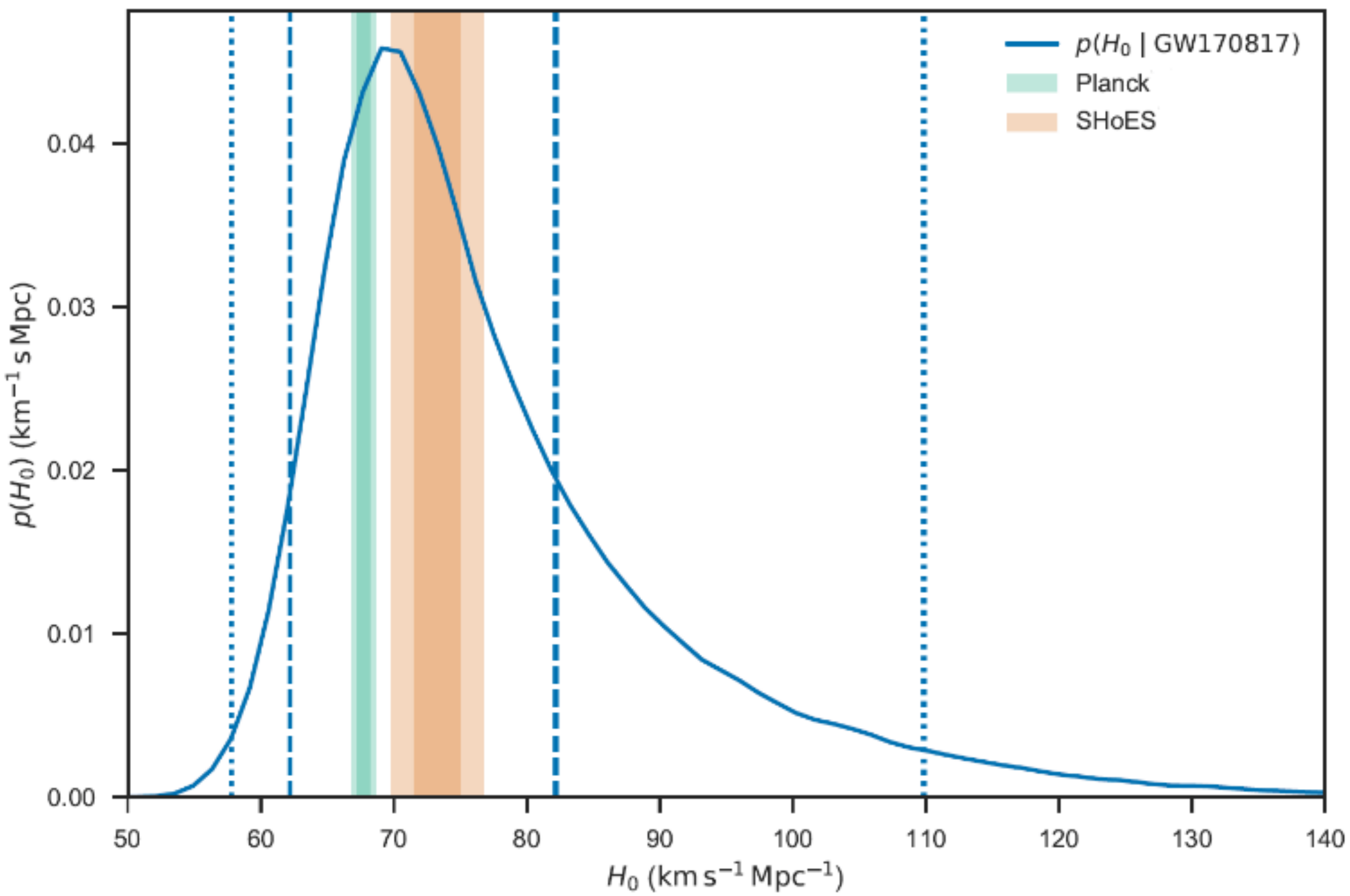


GW170817 EM counterparts





First standard siren measurement of H0

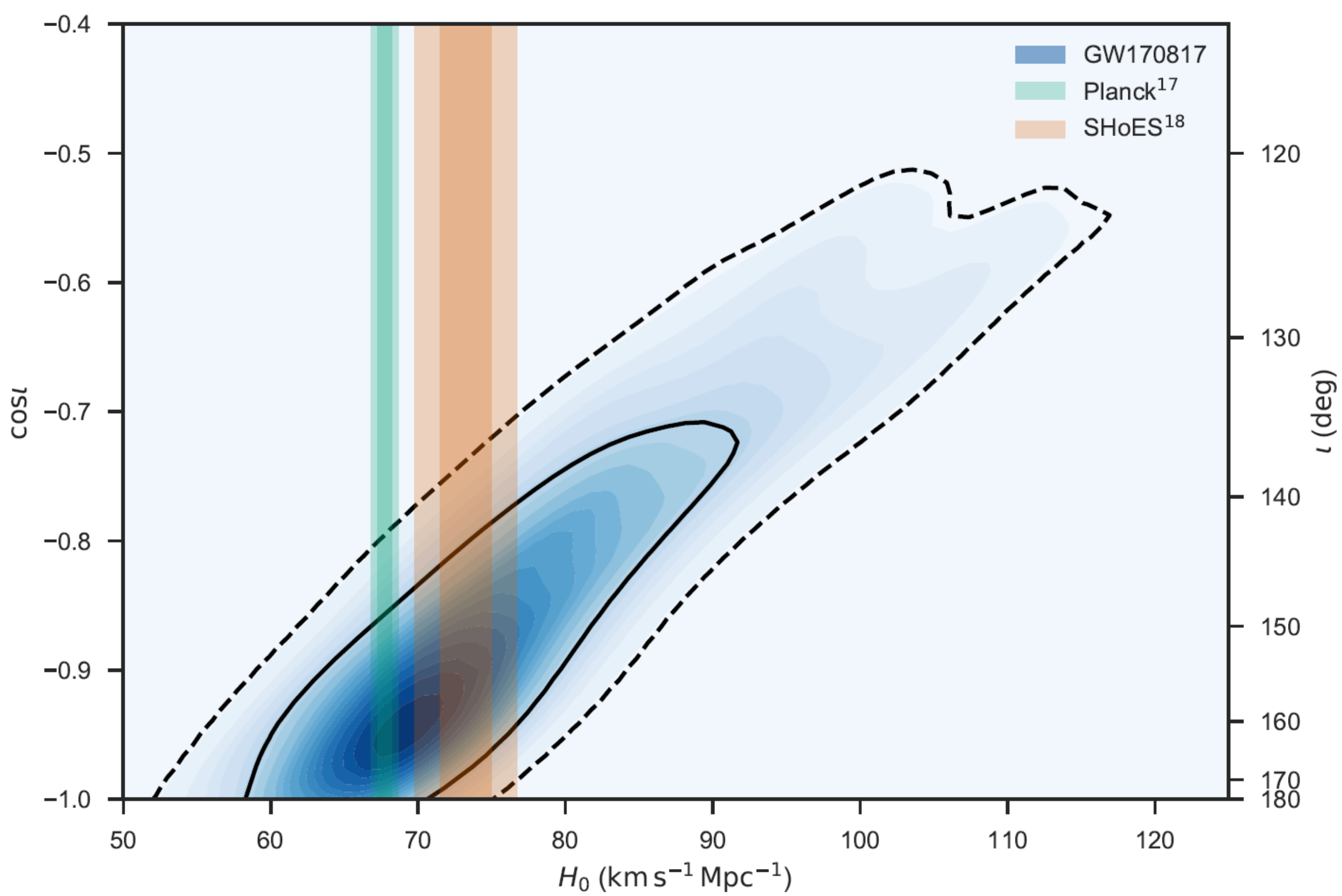


$$H_0 = 70^{+12}_{-8} \text{ km/s/Mpc}$$

- LVC reported a 1-sigma uncertainty of ~14%
- Of this uncertainty:
  - ~11% came from uncertainty in measuring GW luminosity distance.
  - The rest came from uncertainty in the peculiar velocity of the galaxy w.r.t the Hubble flow.

LVC+ 2017

Breaking the inclination degeneracy



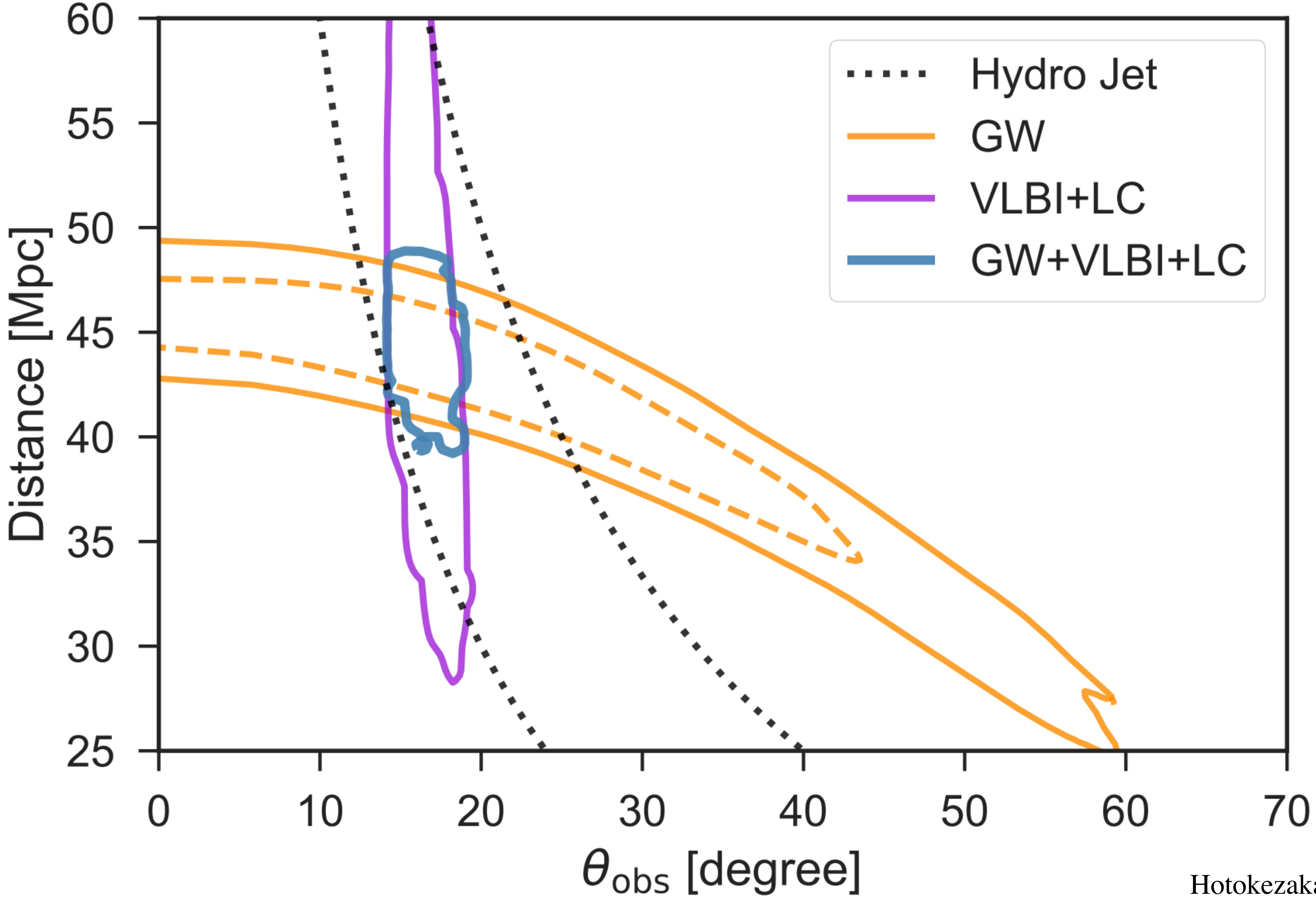
- The luminosity distance enters both polarizations in combination with the orbital inclination angle -> degeneracies

$$h_+ \propto \frac{(\cos\iota + 1)^2}{2D_L}$$

$$h_\times \propto \frac{\cos\iota}{D_L}$$

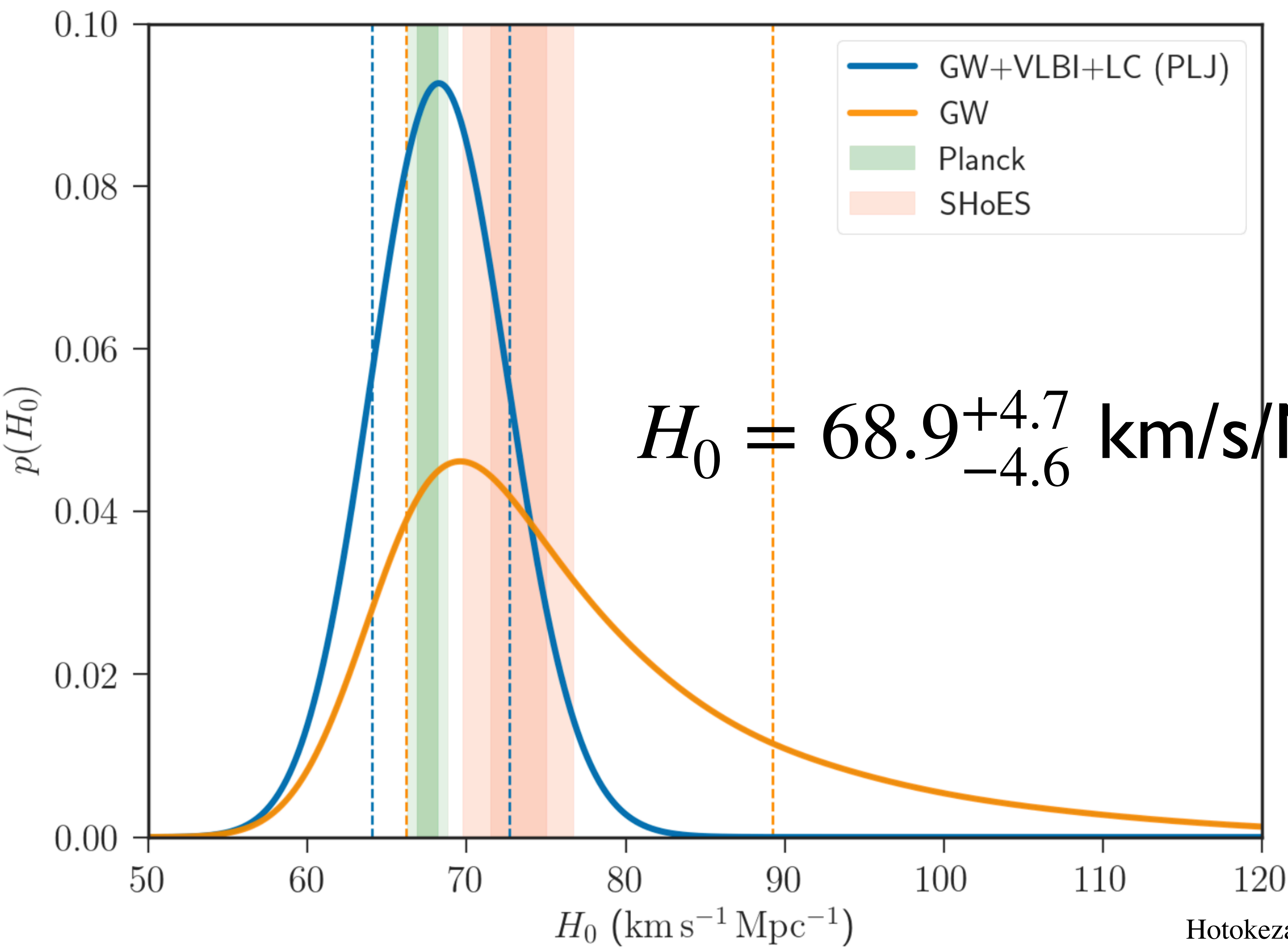
LVC+ 2017

Breaking the inclination degeneracy



Hotokezaka+ 2018

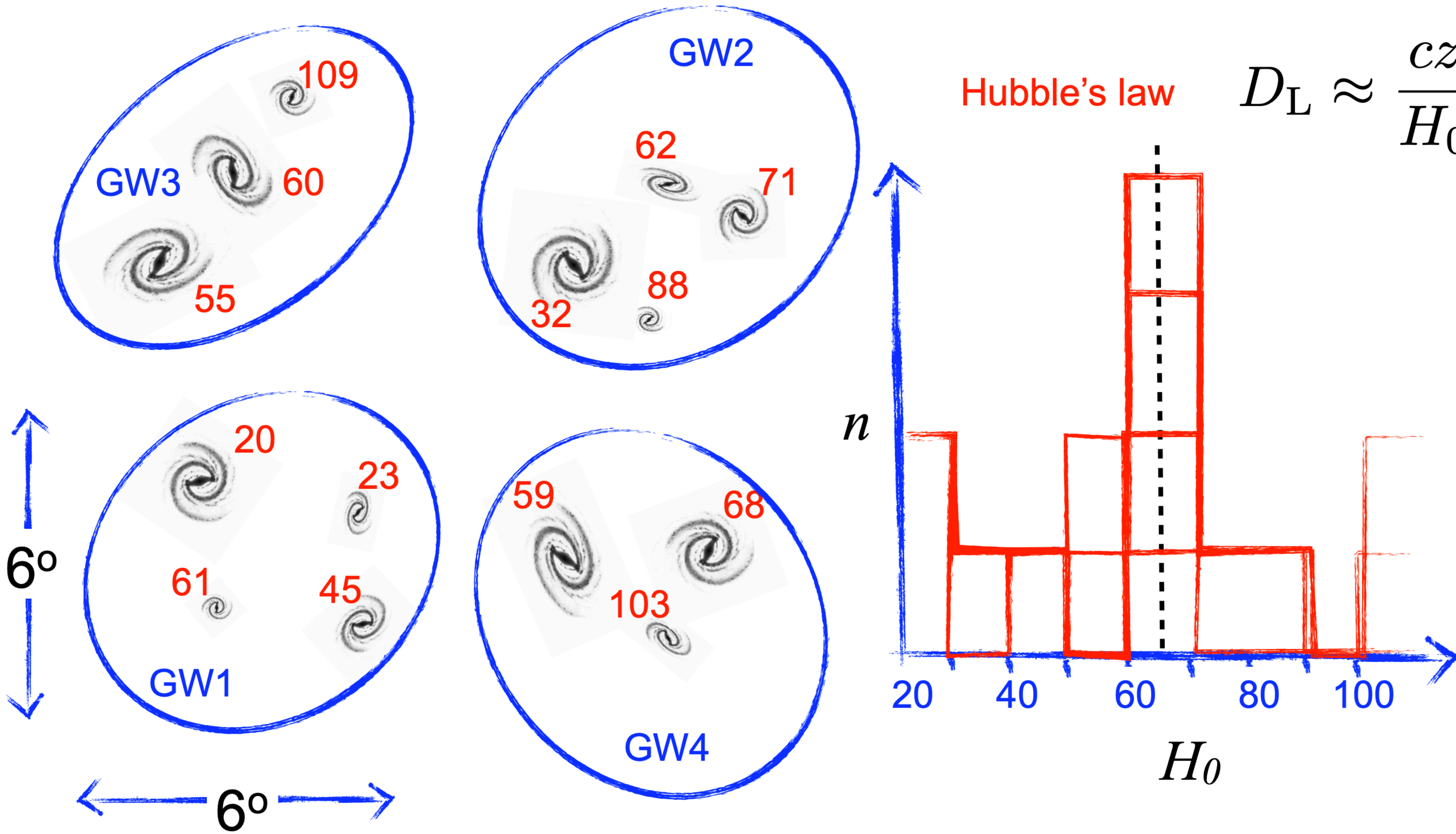
Breaking the inclination degeneracy



$H_0 = 68.9^{+4.7}_{-4.6}$ km/s/Mpc

Hotokezaka+, 2018

Cross correlating with galaxy catalogs



$$D_{\mathrm{L}} \approx \frac{cz}{H_0}$$

Credit: Chris Messenger

Bayesian Formalism

$$p(H_0|\{x_{\mathrm{GW}}\},\{D_{\mathrm{GW}}\}) \propto p(H_0)p(N_{\mathrm{det}}|H_0)\prod_i^{N_{\mathrm{det}}} p(x_{\mathrm{GW}i}|D_{\mathrm{GW}i},H_0)\,.$$

$$p(x_{\mathrm{GW}}|D_{\mathrm{GW}},H_0) = \frac{p(D_{\mathrm{GW}}|x_{\mathrm{GW}},H_0)p(x_{\mathrm{GW}}|H_0)}{p(D_{\mathrm{GW}}|H_0)}$$

$$p(x_{\mathrm{GW}}|D_{\mathrm{GW}},H_0) = \sum_{g=G,\bar{G}} p(x_{\mathrm{GW}}|g,D_{\mathrm{GW}},H_0)p(g|D_{\mathrm{GW}},H_0)\,.$$

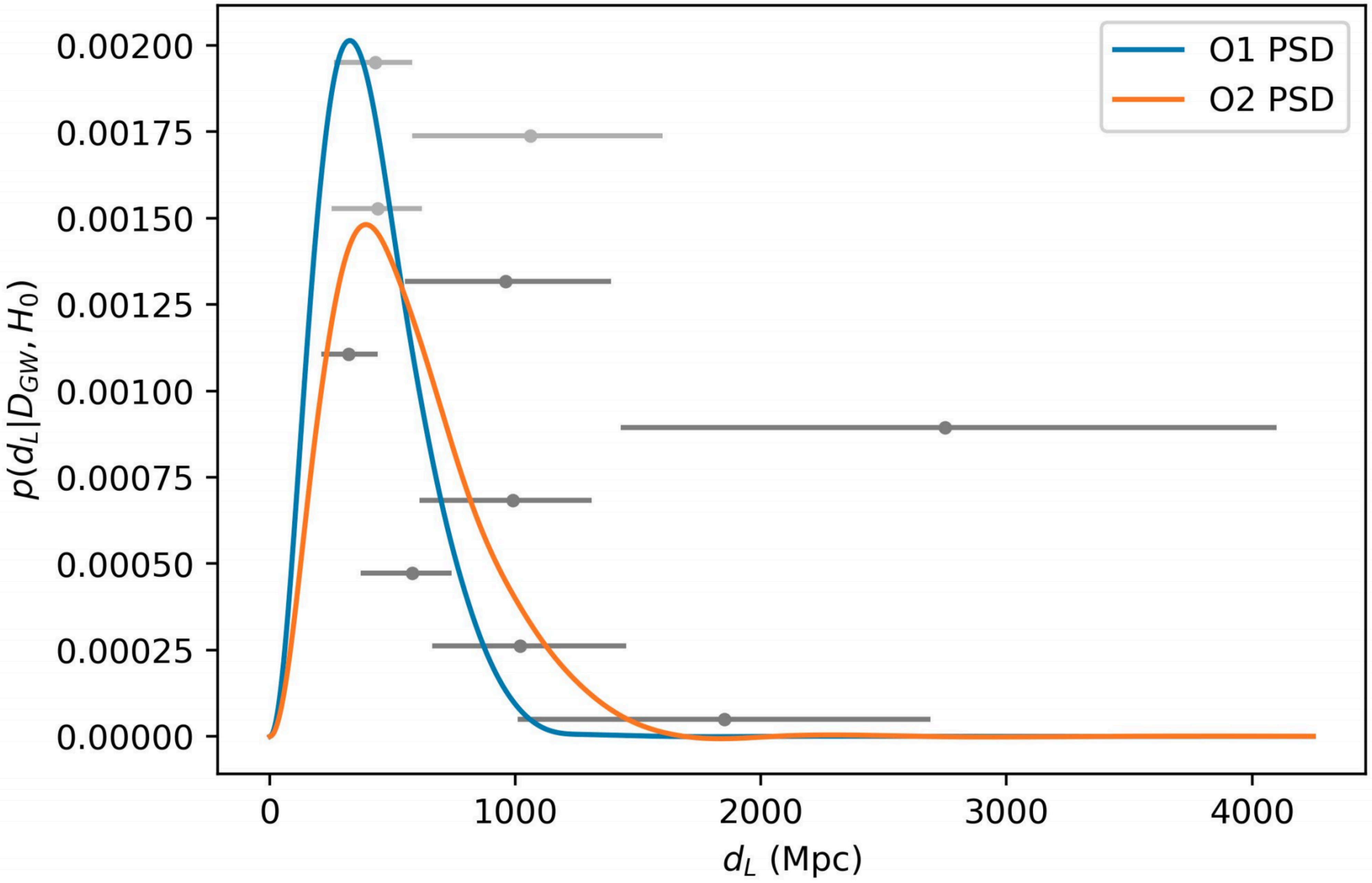
Selection Effects

In catalog

Out of catalog

Gray, Magaña Hernandez+ arXiv:1908.06050

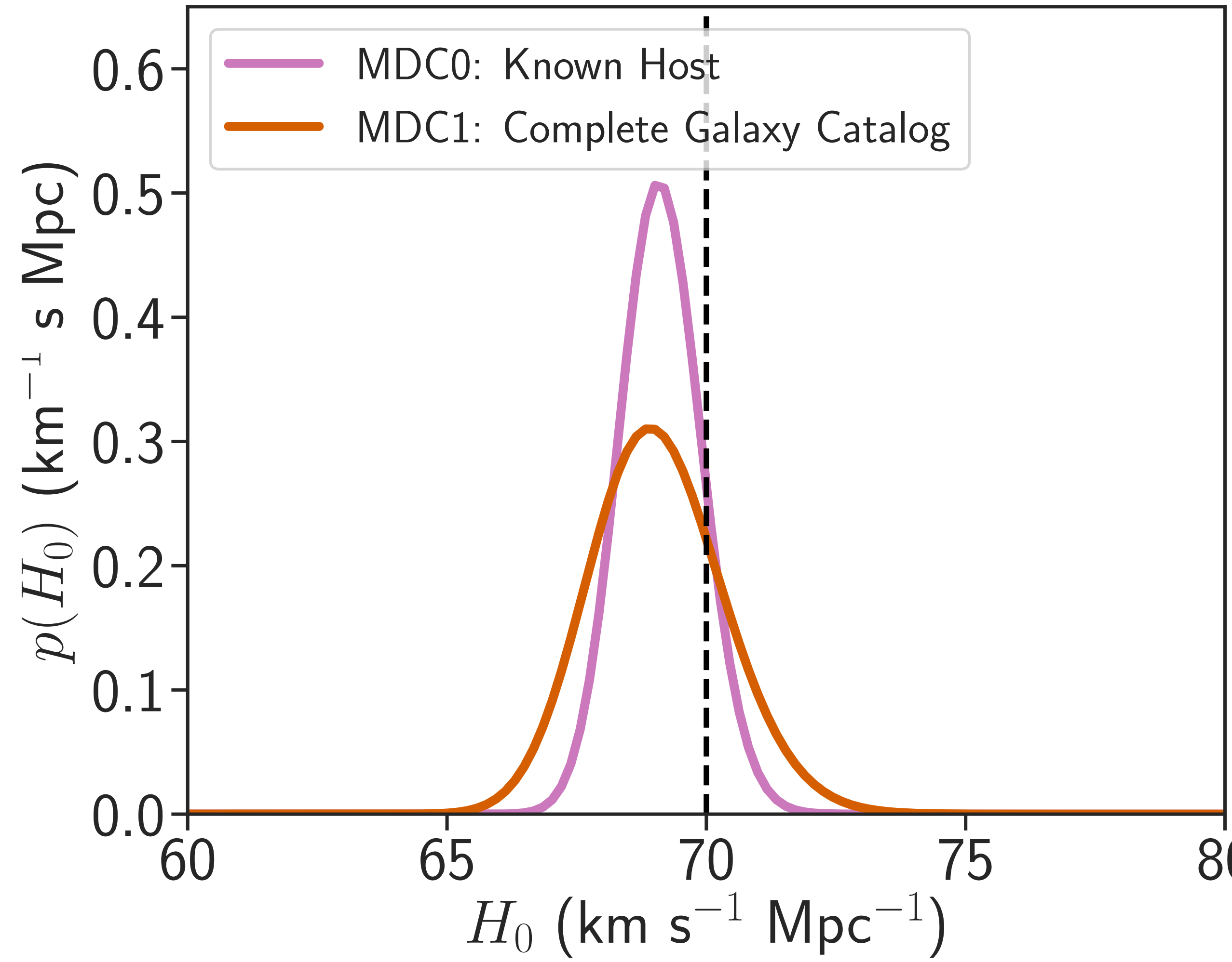
Selection Effects



Credit: Rachel Gray

Mock data studies

- Use LIGO's First Two Years dataset:
    - End-to-end simulation of 250 BNS events at O2 like sensitivities.
    - Full parameter estimation for each event available.
- Simulate a complete galaxy catalog based on the injected coordinates for each event.
    - Complete out to ~450Mpc, with euclidian cosmology used to simulate catalog (used for First Two Years simulations).



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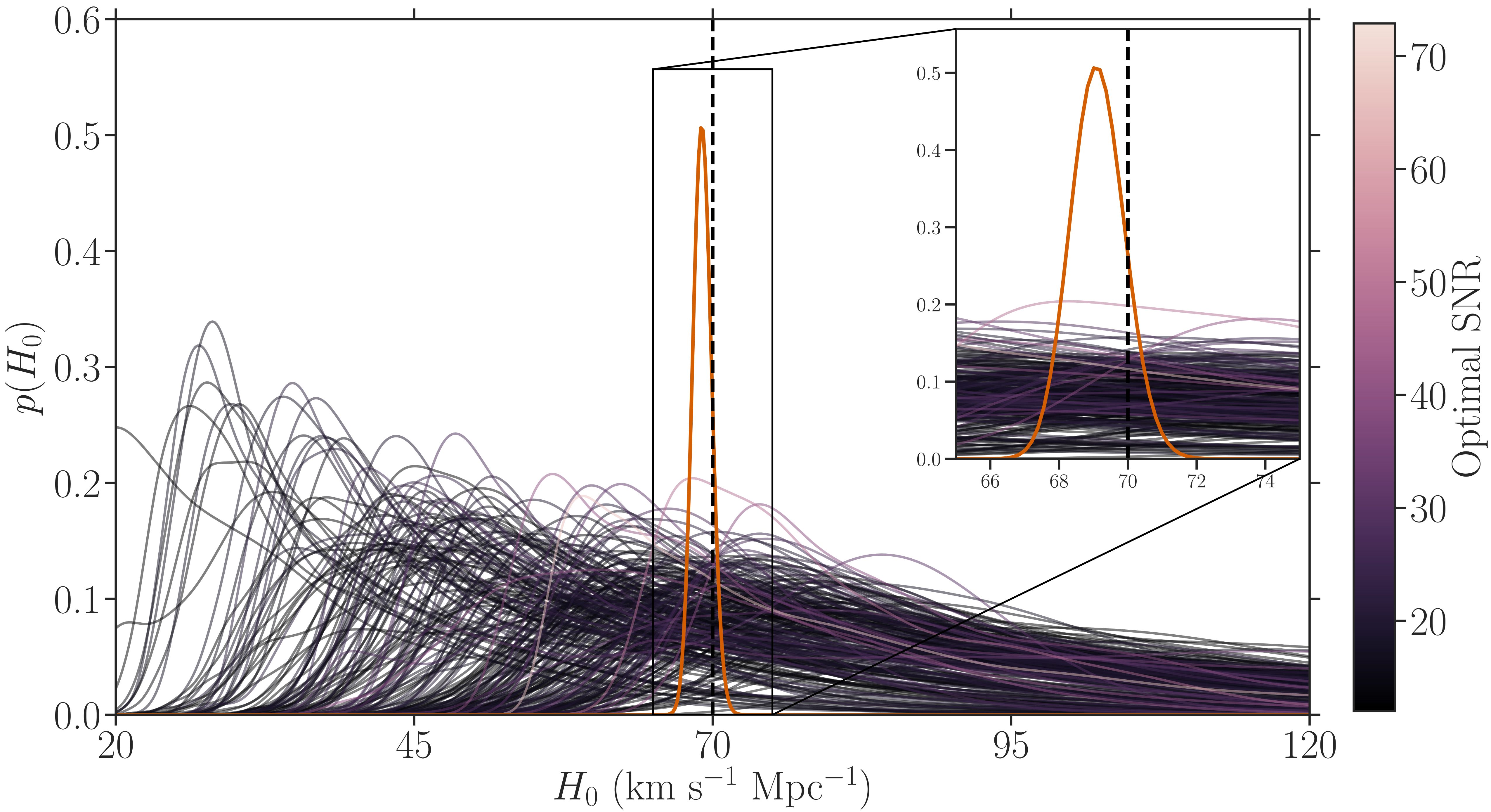
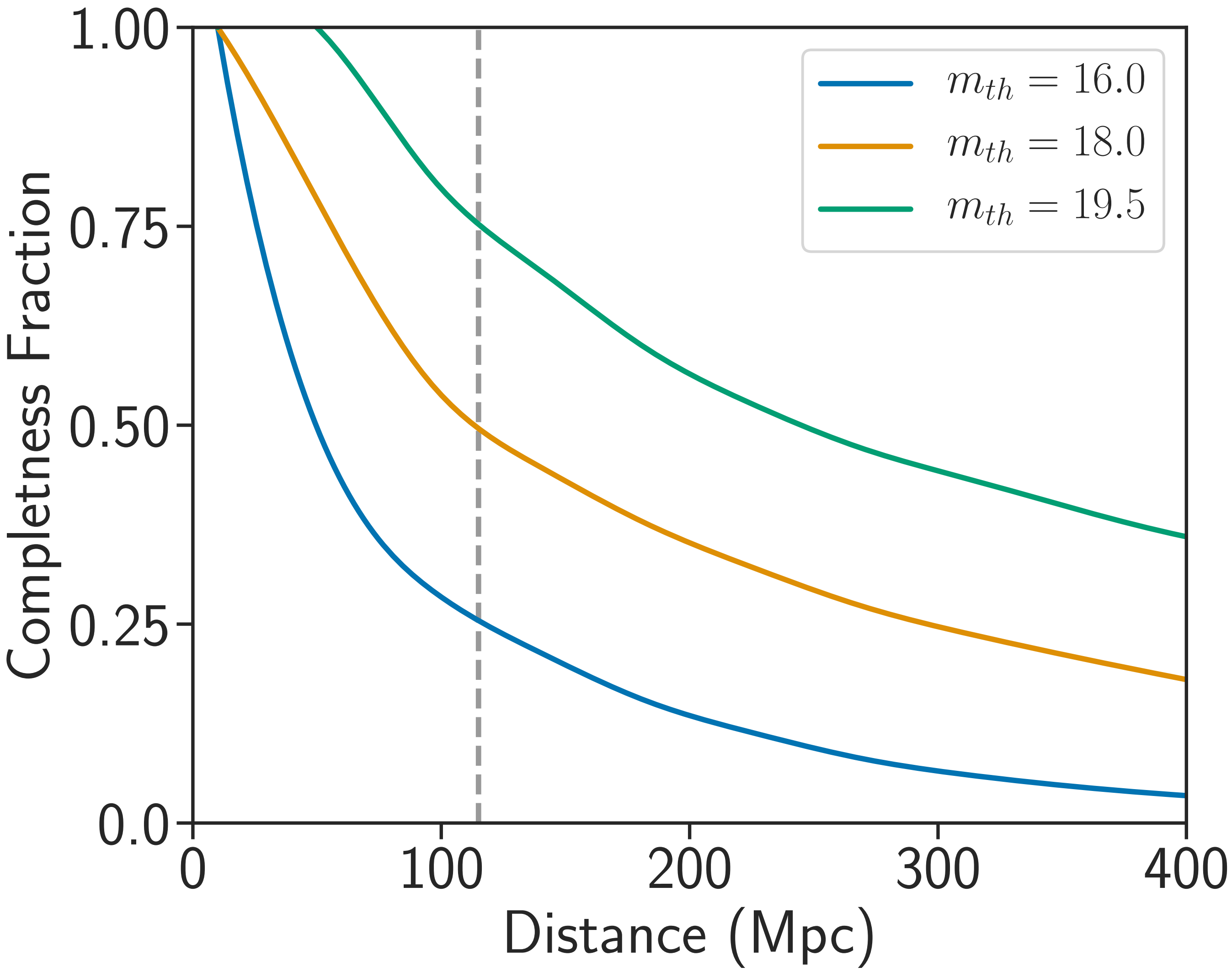


Gray, Magaña Hernandez+ arXiv:1908.06050

Mock data studies

- Most galaxy catalogs are not complete.
  - Simulate completeness by setting an apparent magnitude threshold.
  - We look at 75%, 50% and 25% completeness fractions here.
  - Expect incompleteness of catalog to dominate the uncertainty of the statistical method.



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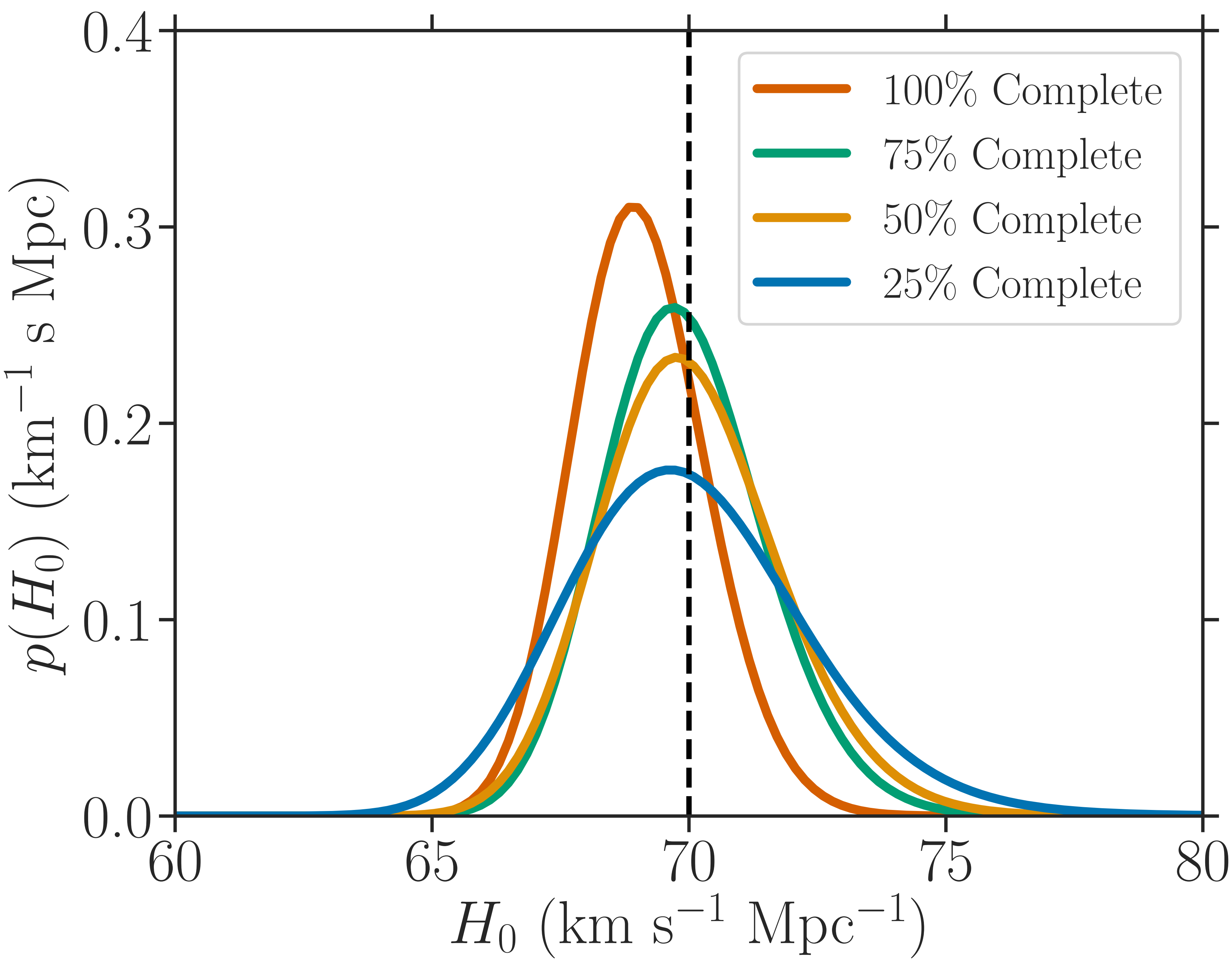
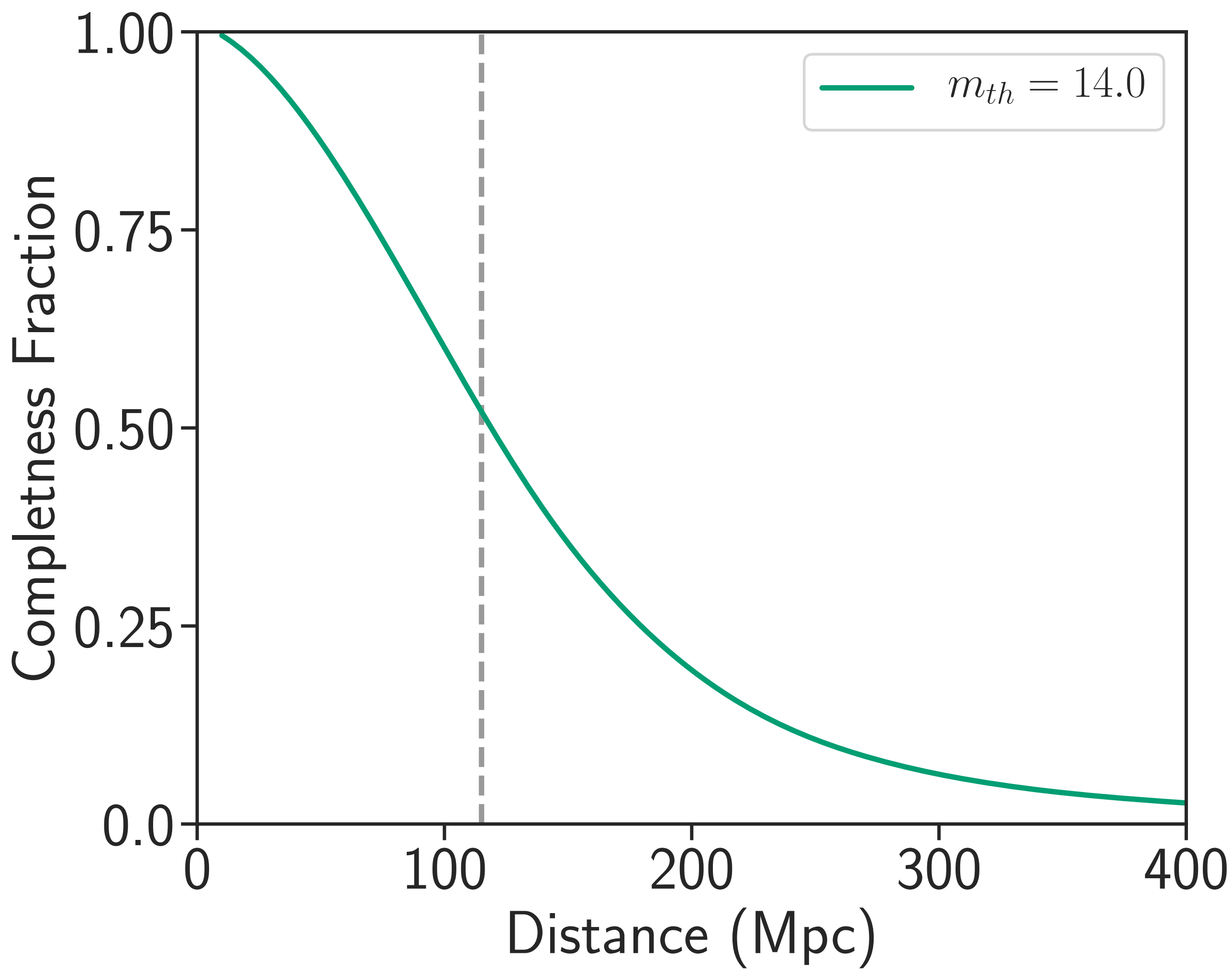


Gray, Magaña Hernandez+ arXiv:1908.06050

Mock data studies

- We expect BNS merger to be biased tracers of star-formation and or the stellar mass.
- Can 'luminosity weight' galaxies as a proxy.
    - Blue galaxies, proxy for star-formation
    - Red galaxies, proxy for total stellar-mass
- Assign a luminosity to simulated BNS mergers so that they are more likely to occur in luminous galaxies



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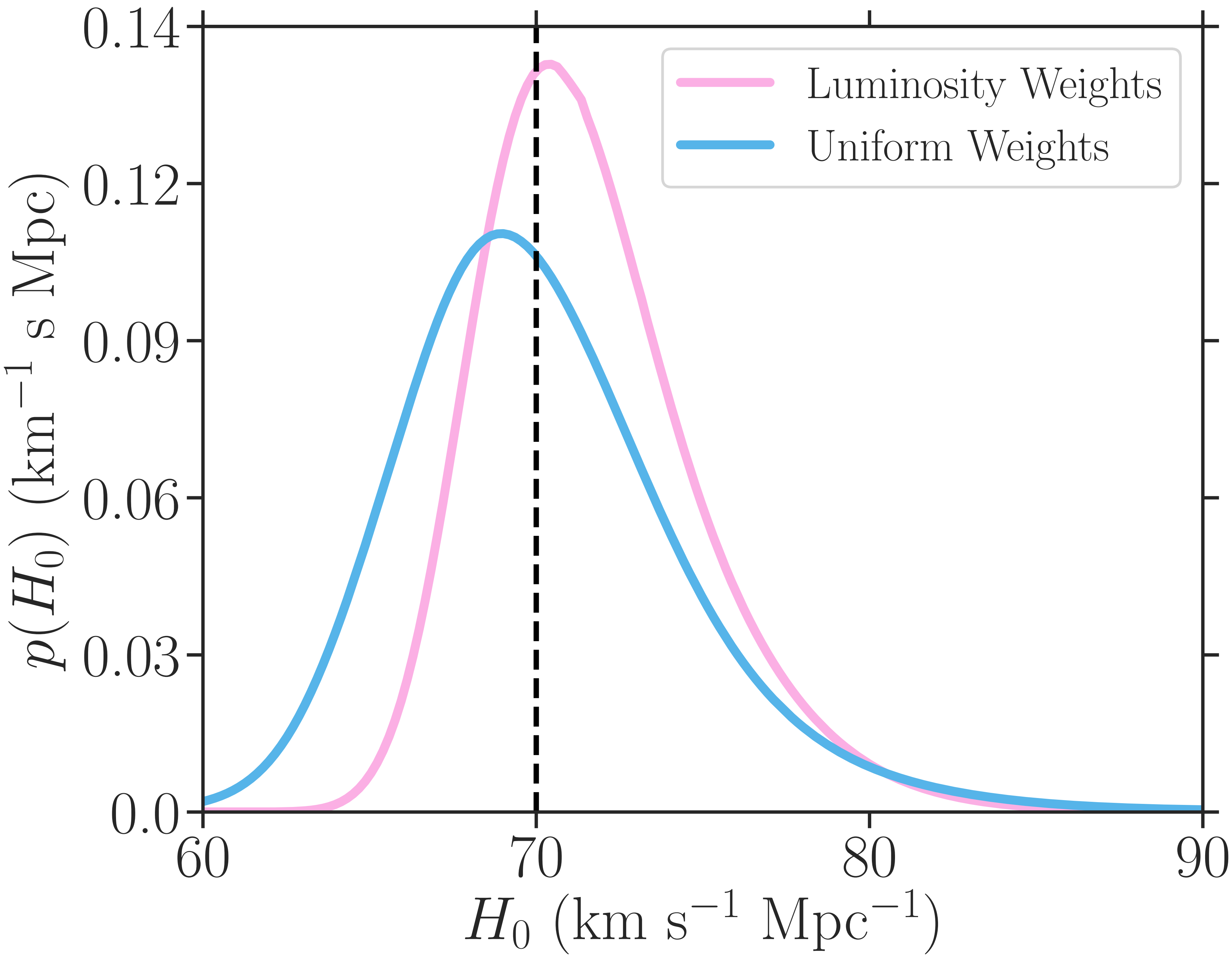

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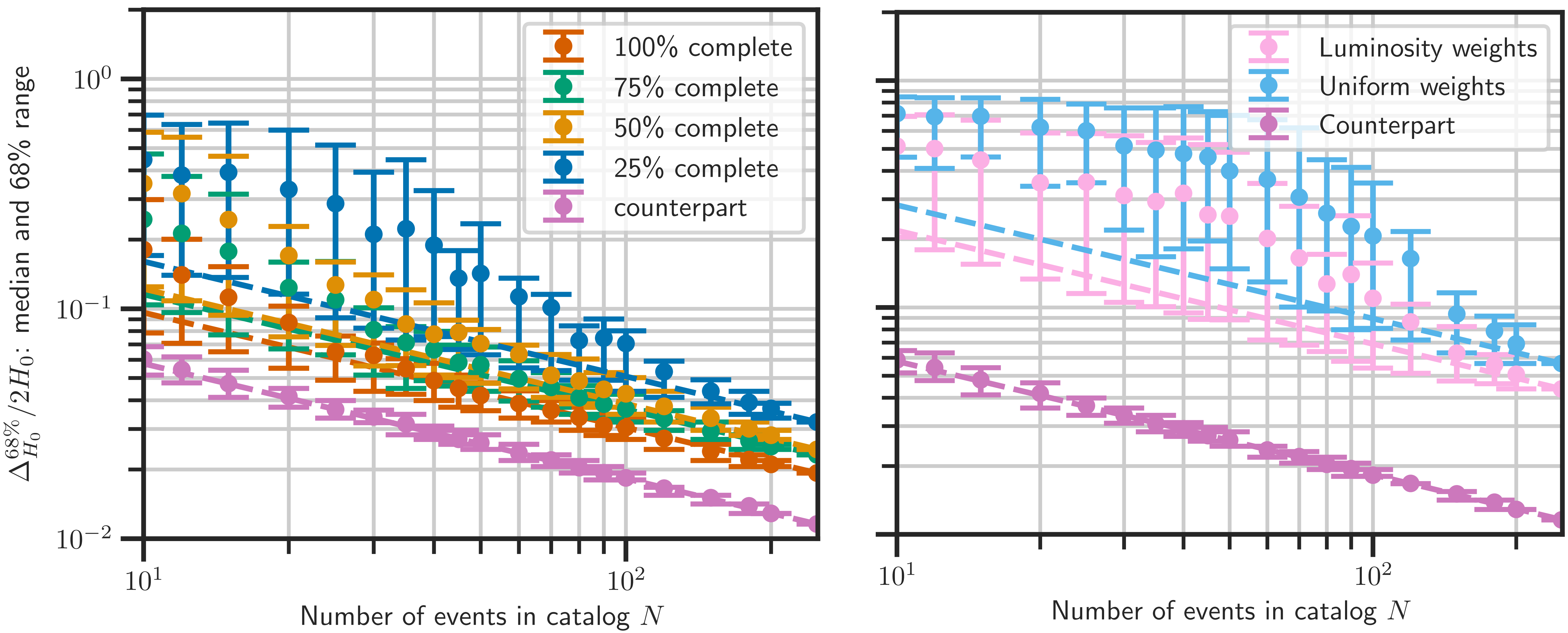
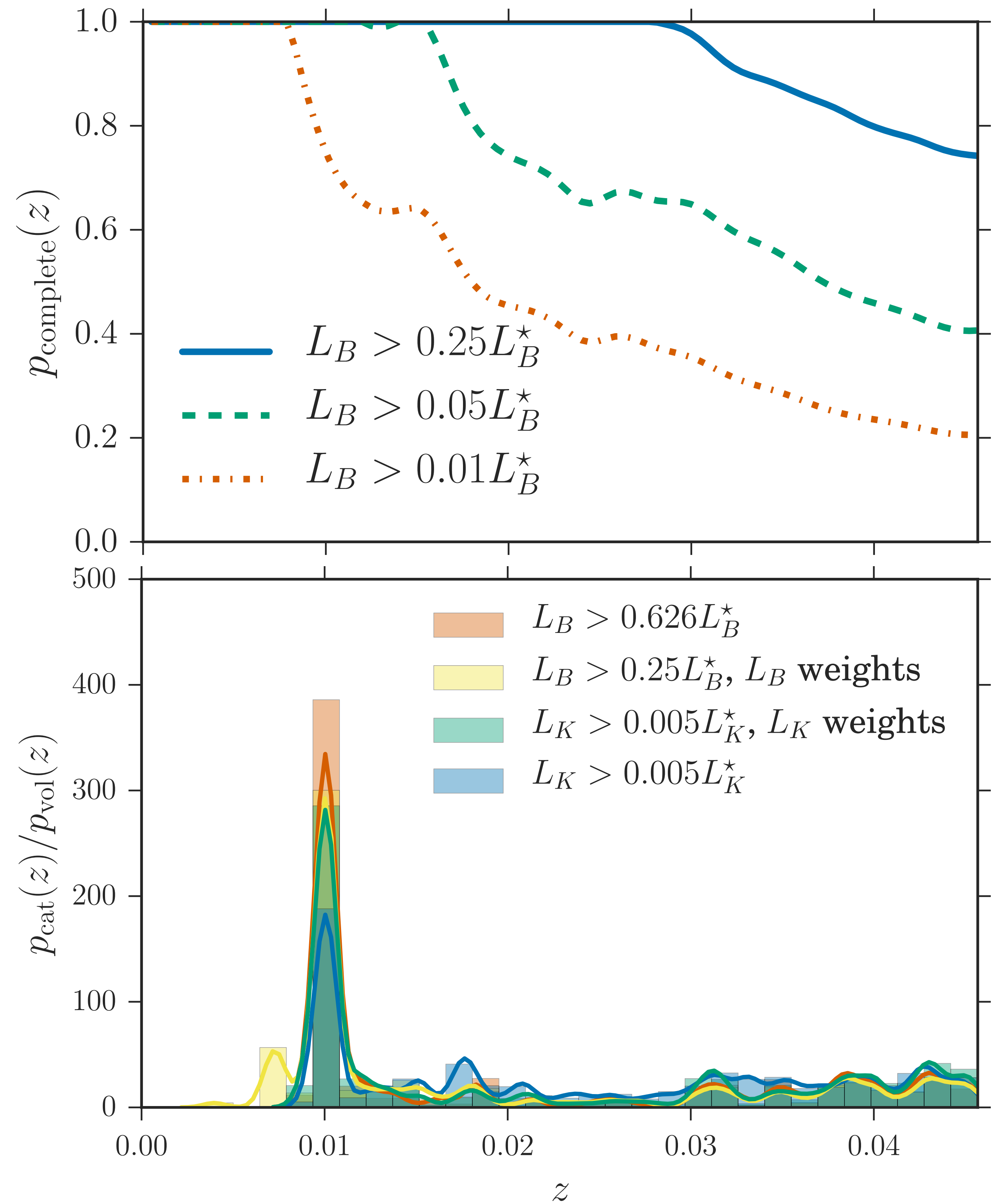


Gray, Magaña Hernandez+ arXiv:1908.06050

GW170817 statistical H0: Galaxy catalog

- First application of the statistical method to a real GW event.
- In here we pretend we don't know the location of the GW event (at z~0.01).
- We use the GLADE galaxy catalog for cross correlation, around 50% complete out to 120 Mpc.
- Single dominant group of galaxies containing NGC 4993



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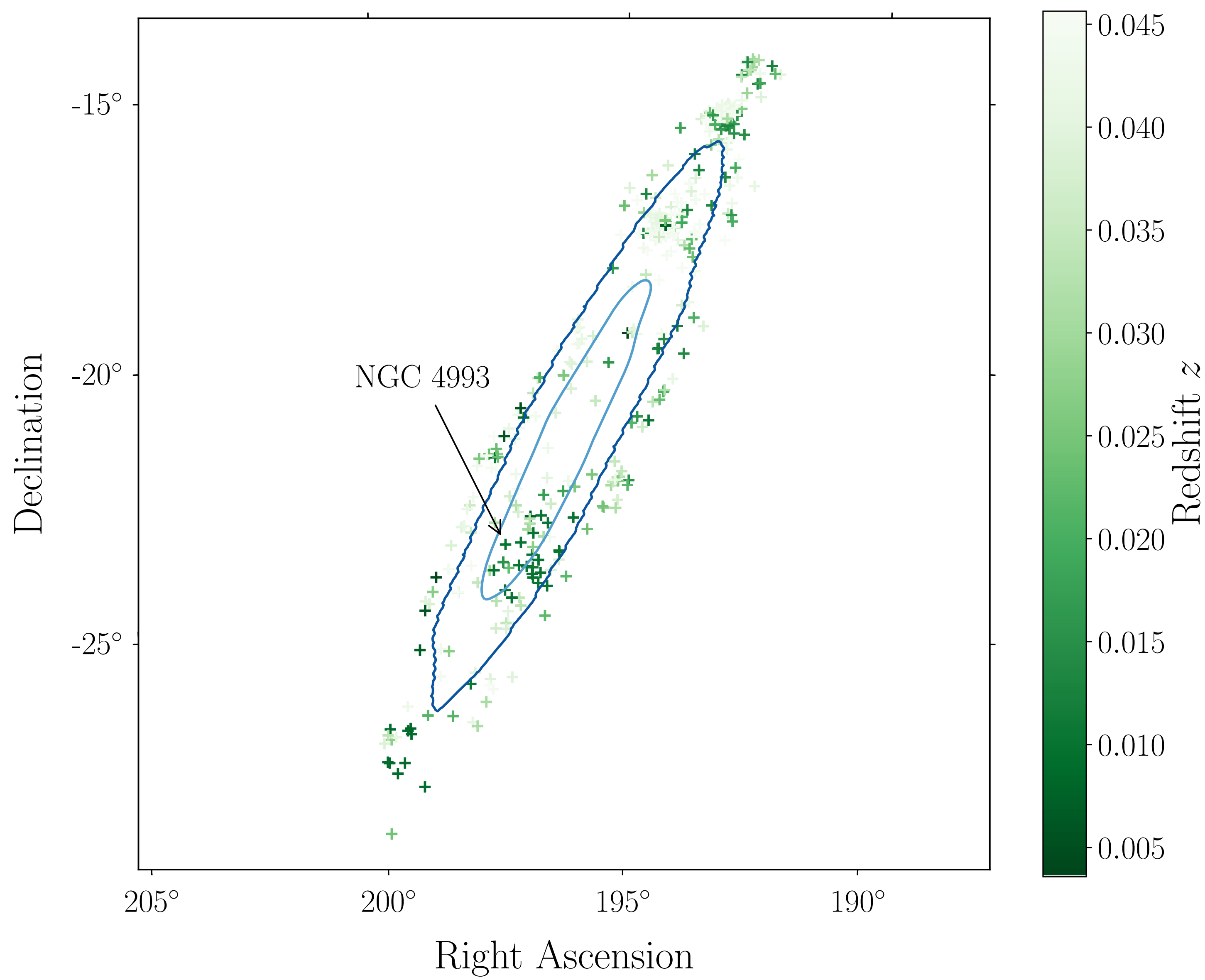
GW170817 statistical H0: Localization



- Galaxies that contribute to the statistical cross correlation with GLADE using the 99% GW170817 localization region within the redshift range $0 < z < 0.046$.

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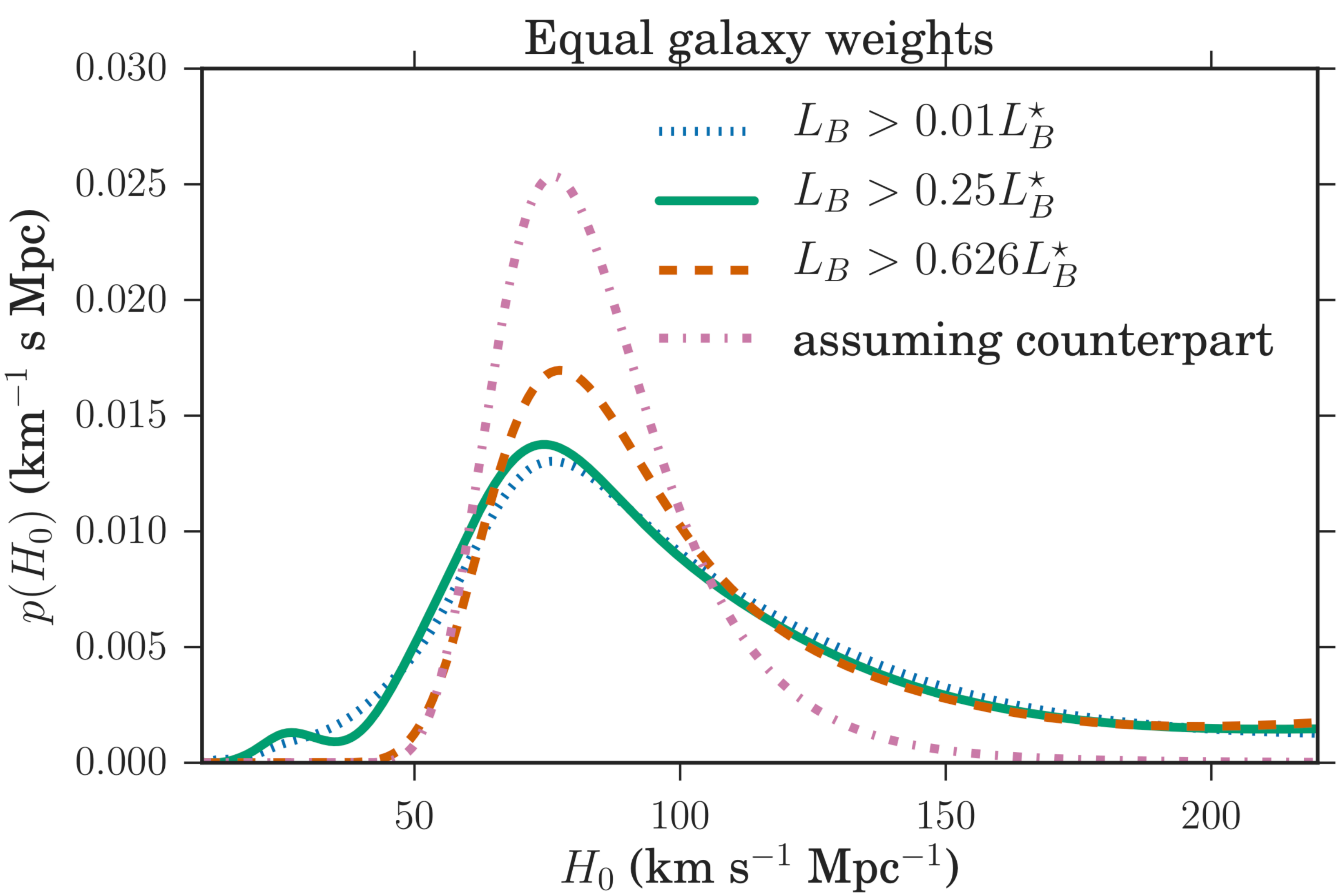
GW170817 statistical H0: Results



Statistical measurement is only ~2 times as broad as counterpart measurement

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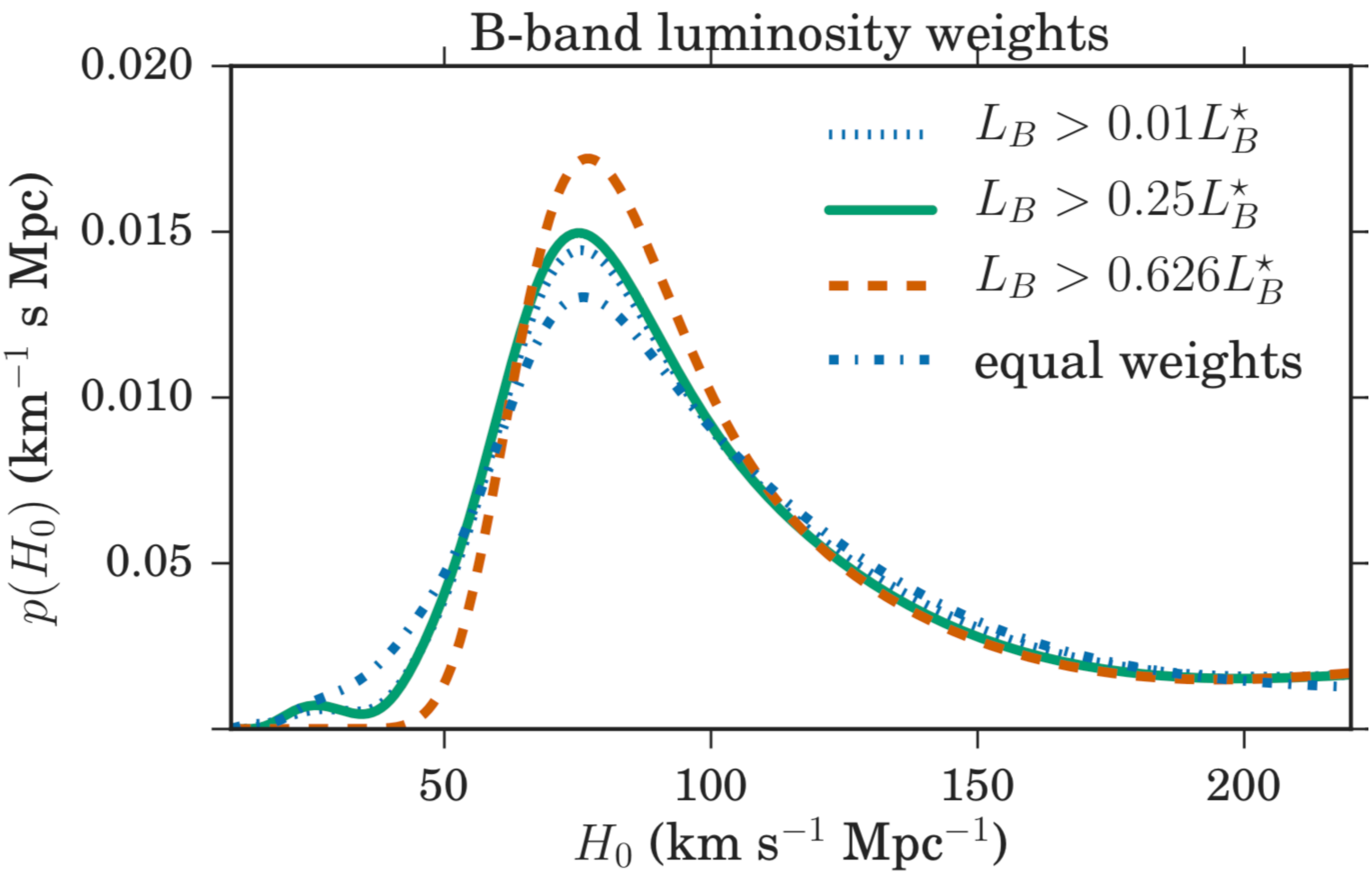
GW170817 statistical H0: Results



Star-formation weights

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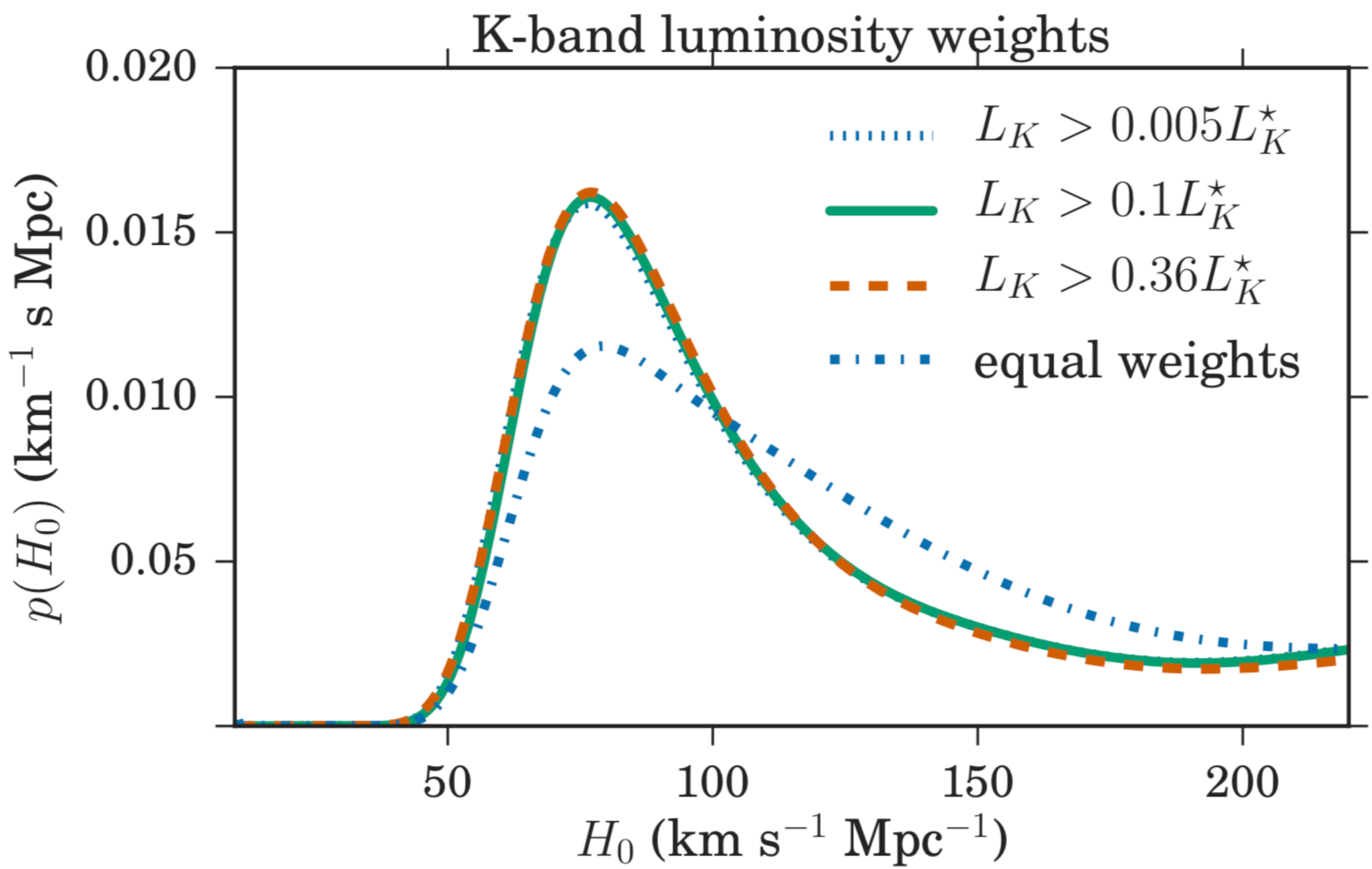
GW170817 statistical H0: Results



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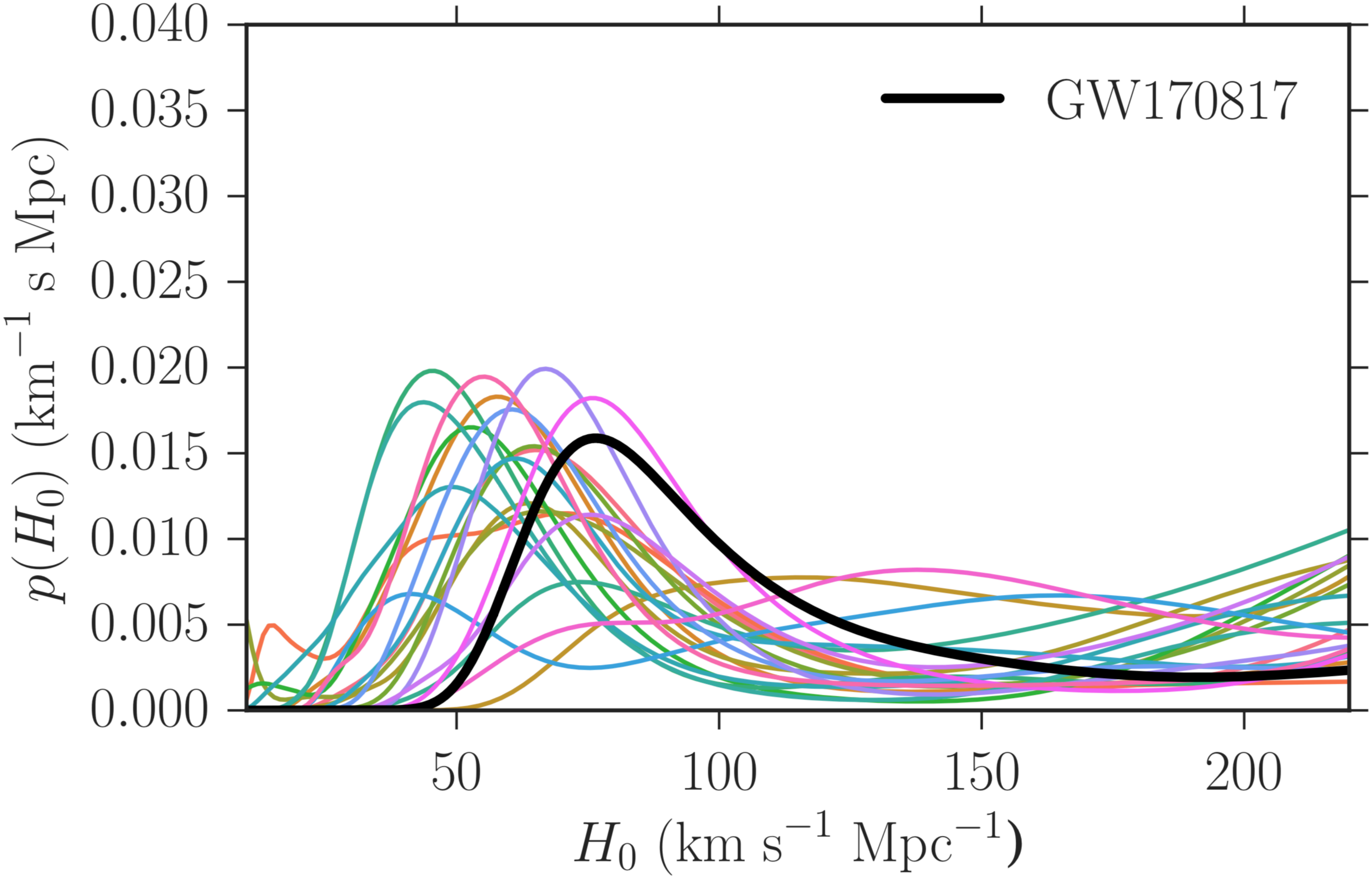
Stellar mass weights

How good was GW170817?



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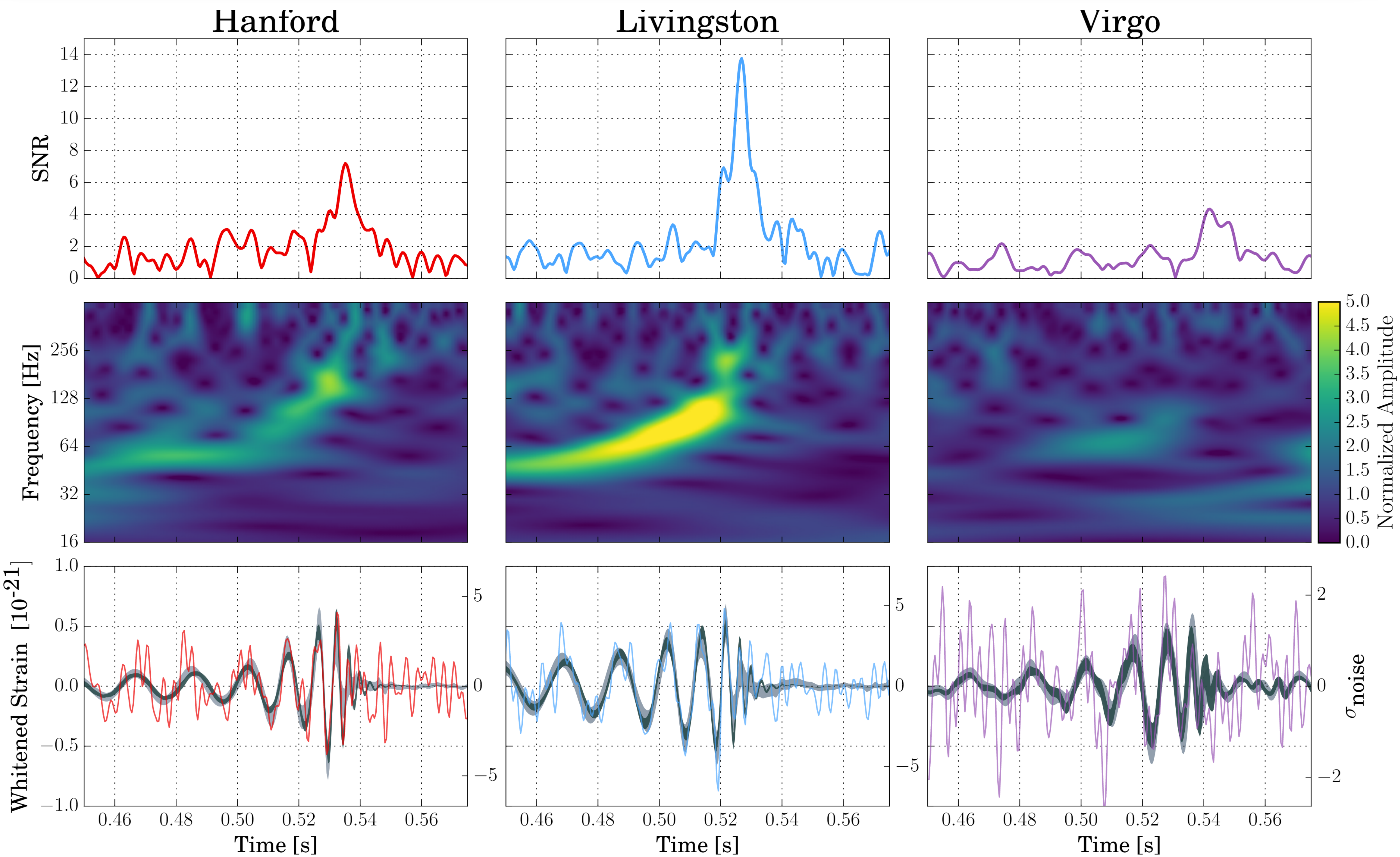
GW170814 - Triple BBH detection

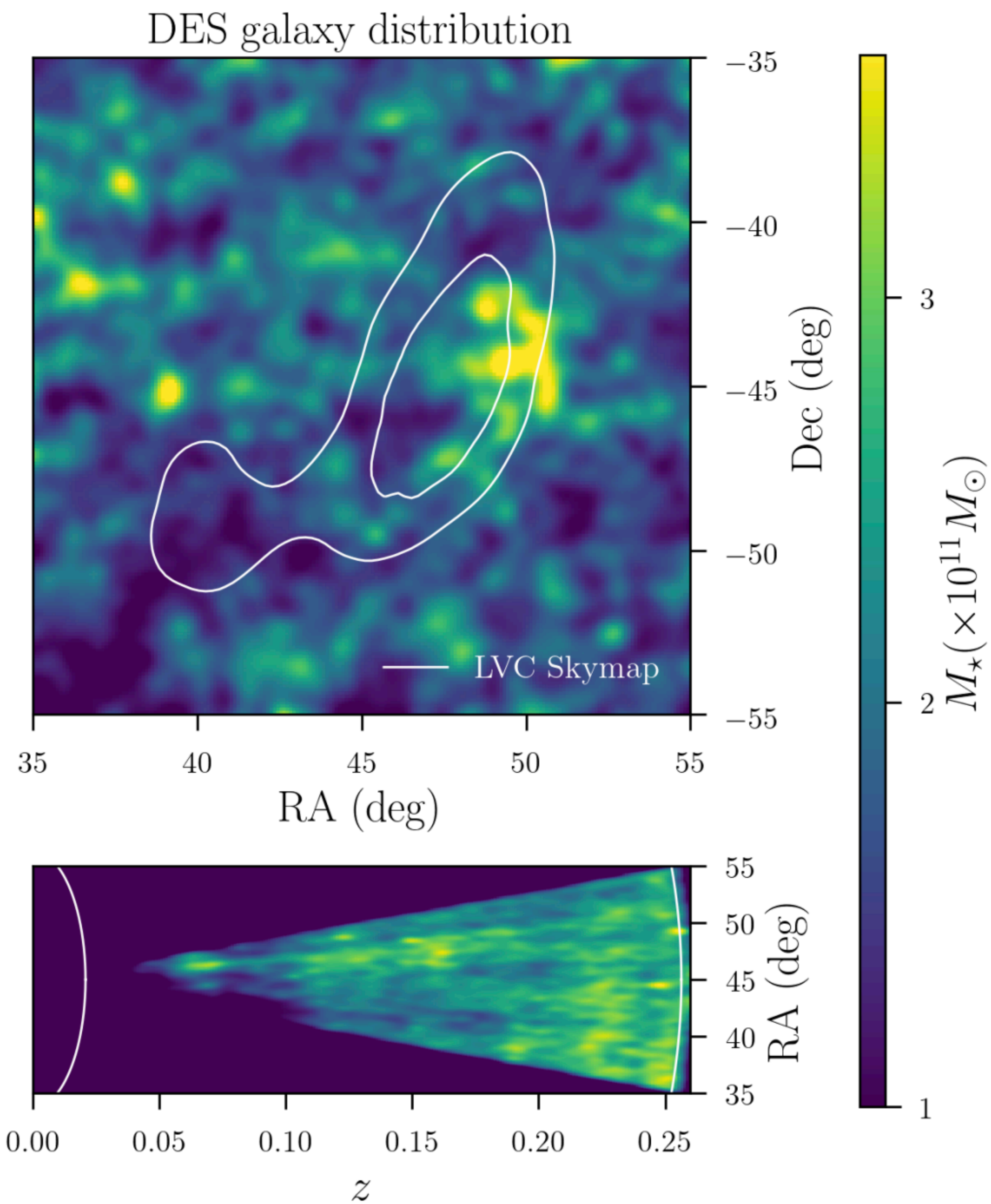


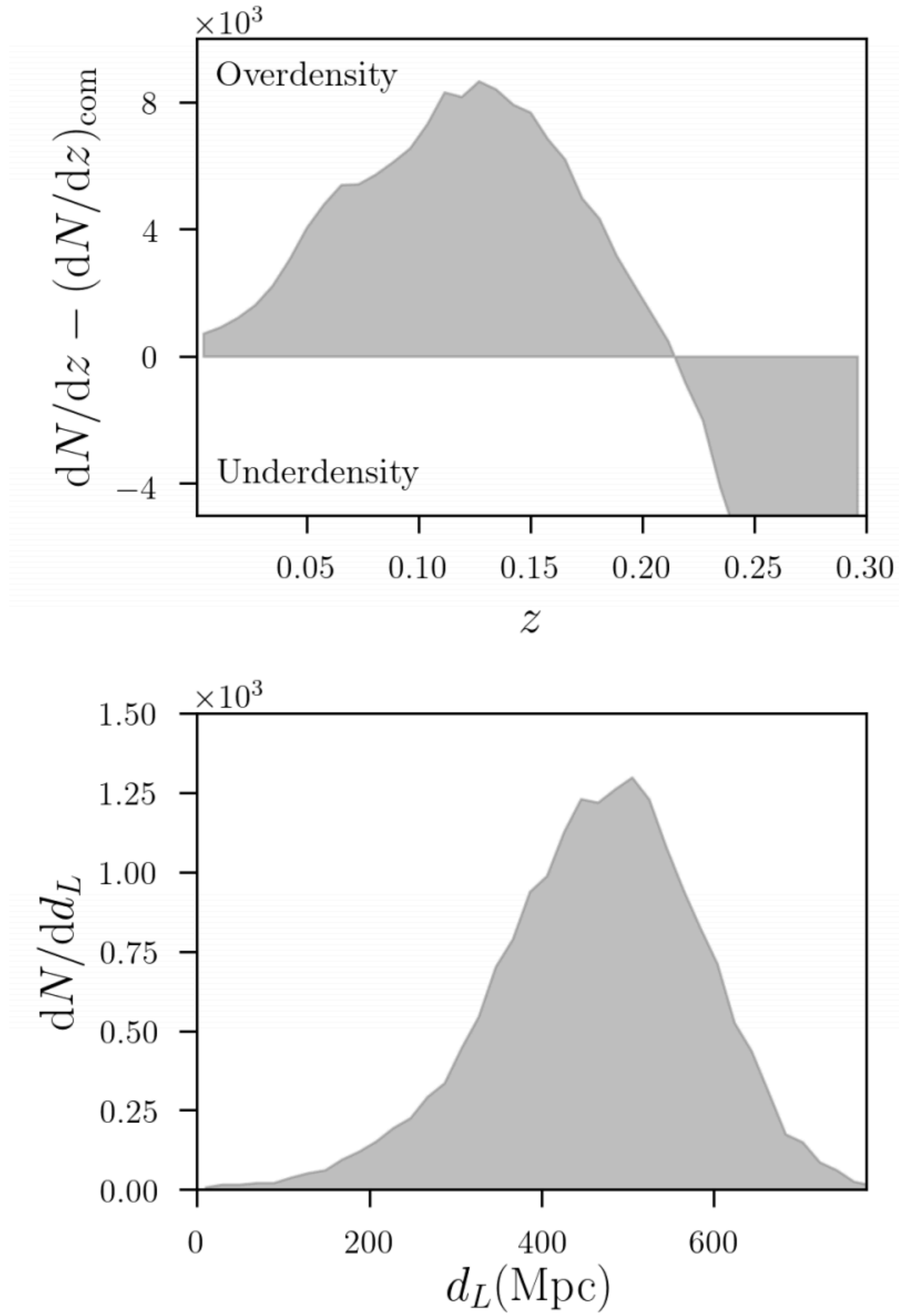
LVC+ 2017

GW170814

- First application of the statistical method to a binary black hole event, "dark siren".
- We used the DES Y3 data, as well as the GW170814 localization data.
- No EM information for BBH events, statistical method **might be the only** realistic way of constraining cosmology with BBHs.
- Measurement dominated by photometric redshift uncertainties and high incompleteness fractions of galaxy catalog at high redshift, e.g. for GW170814, one must consider galaxies out to z~0.3 given H0 prior.

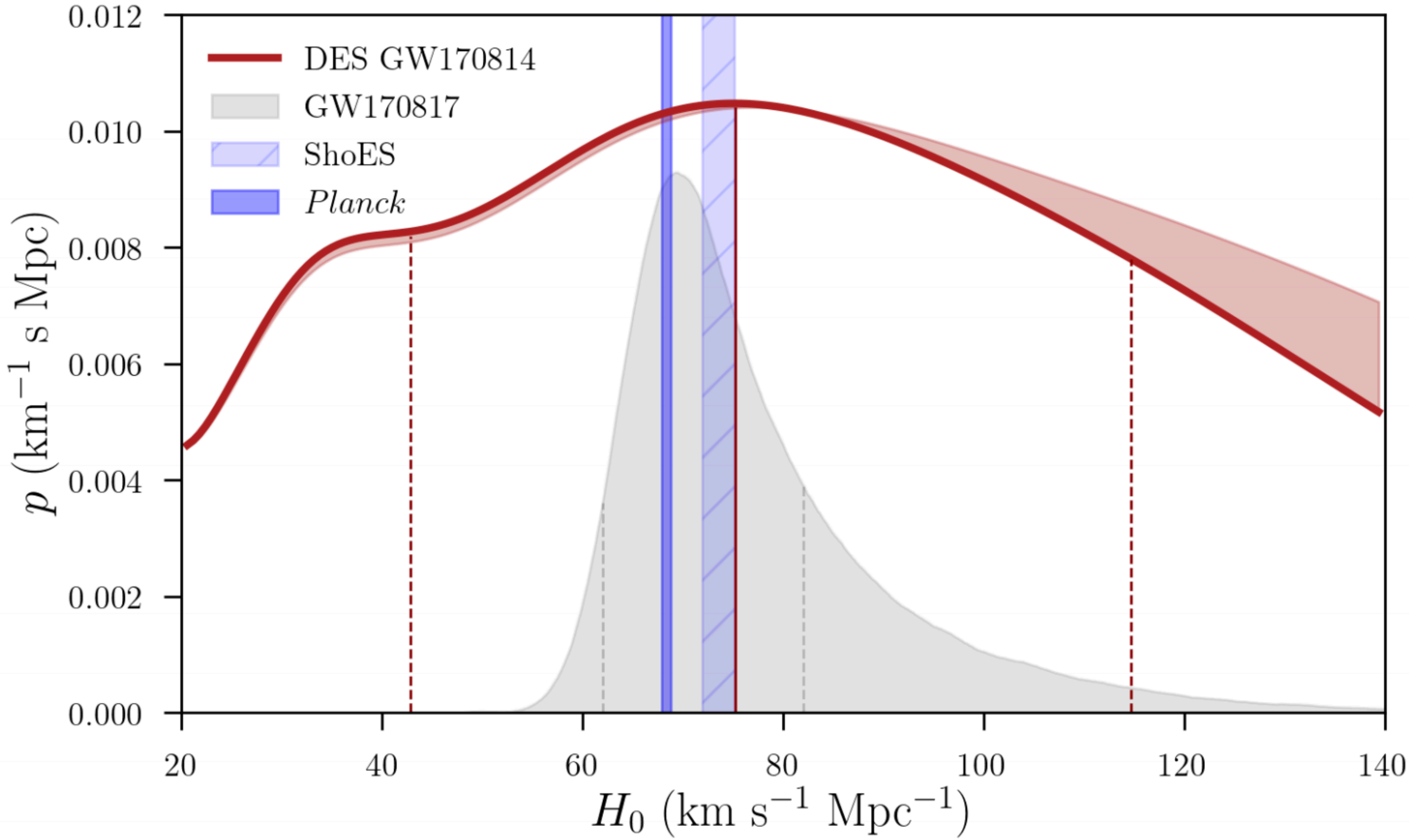
GW170814





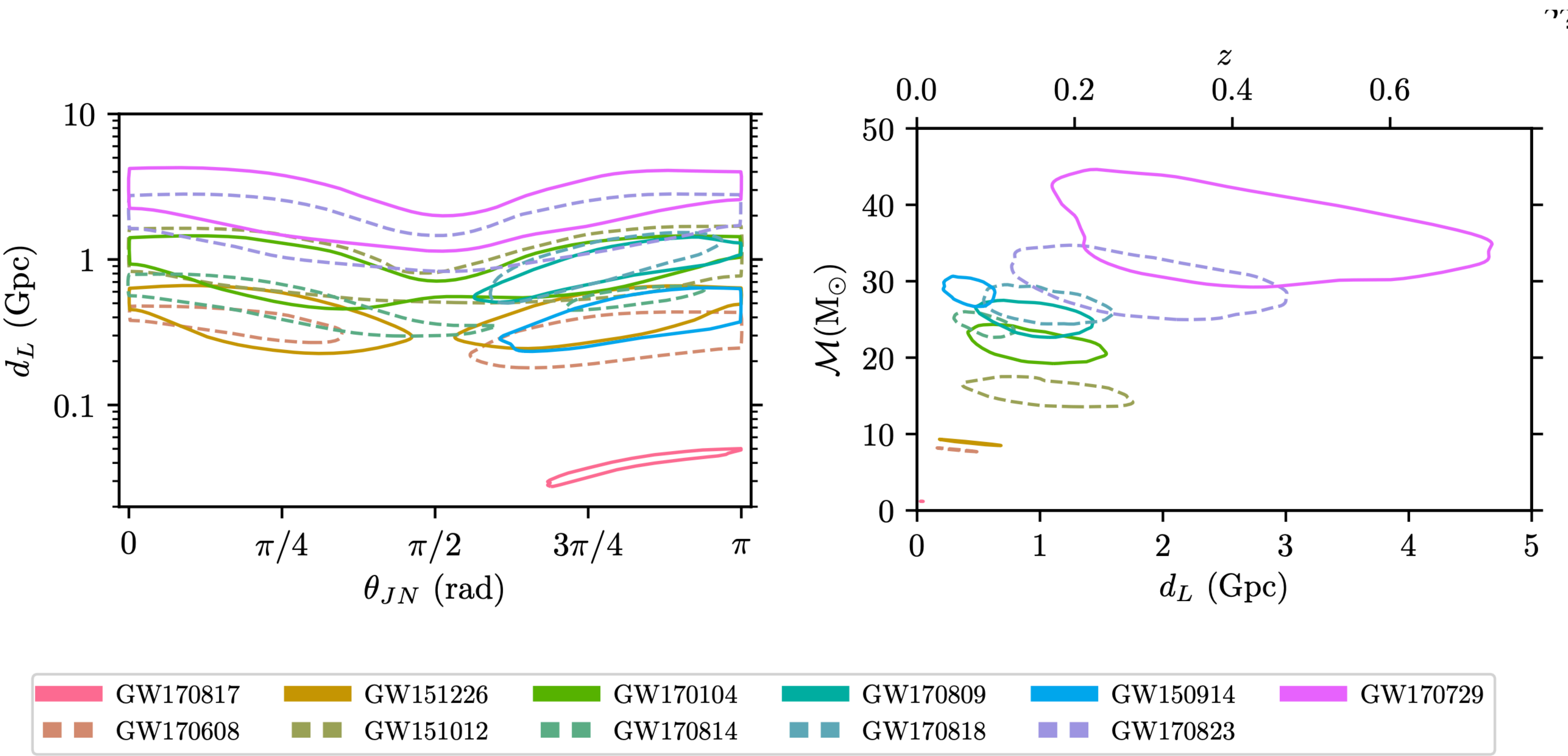
DES, LVC 2019

GW170814

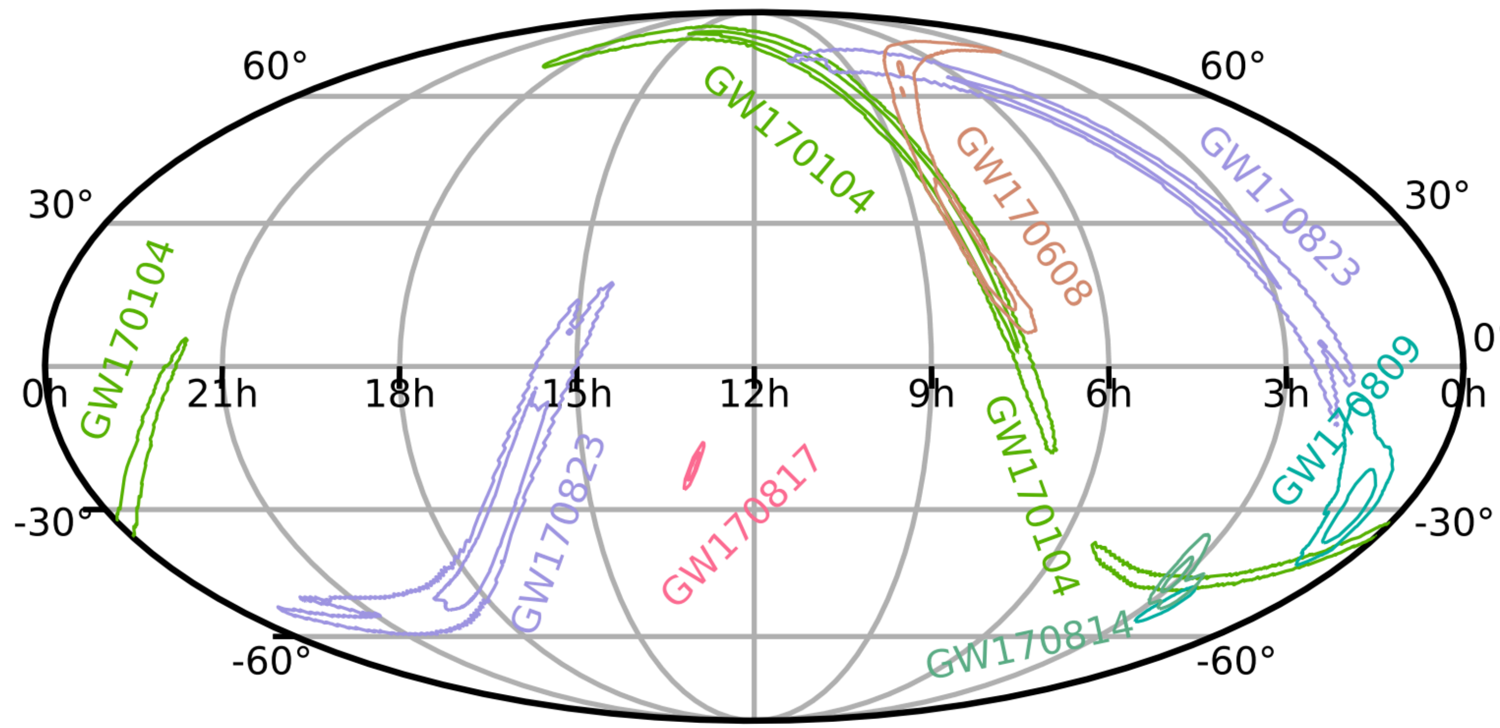


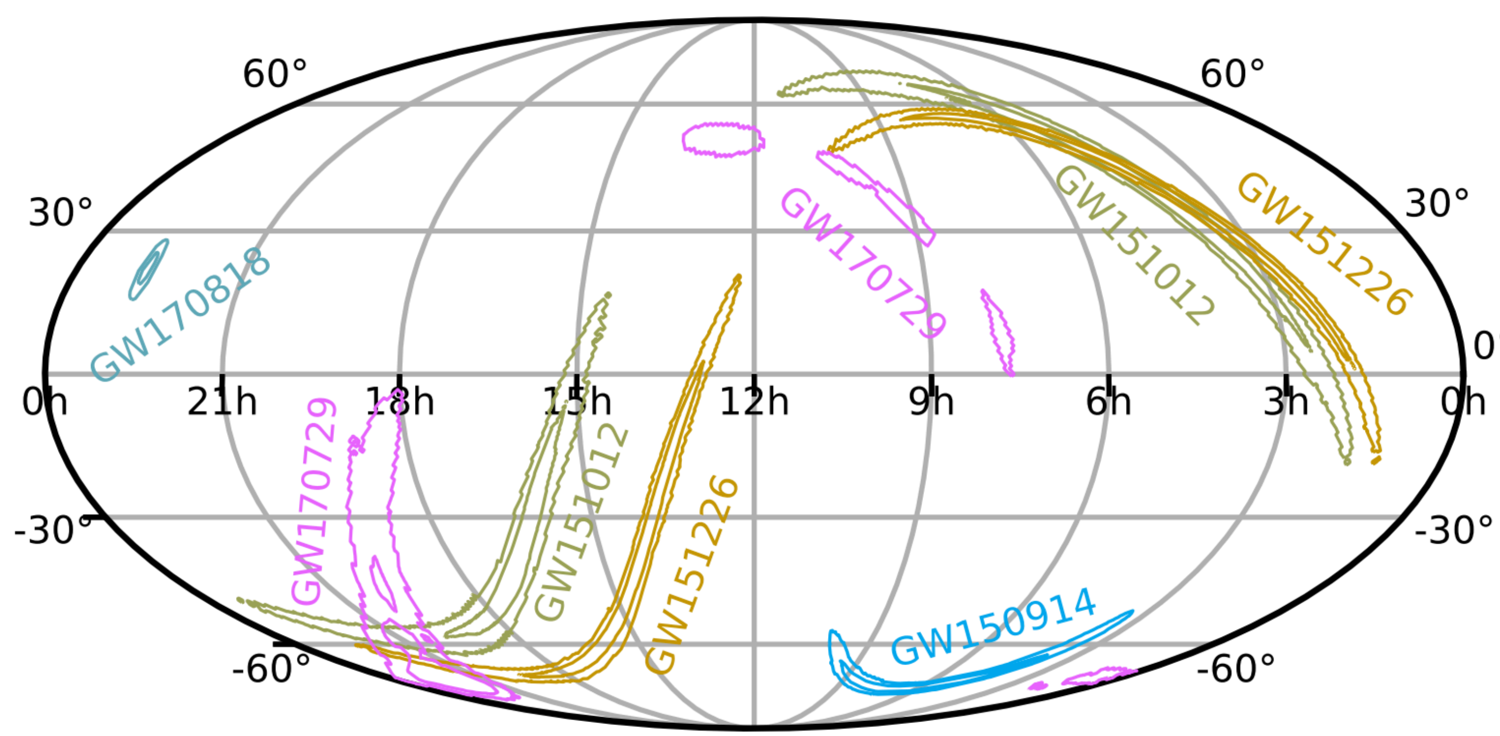
DES, LVC 2019

GWTC-1 Analysis



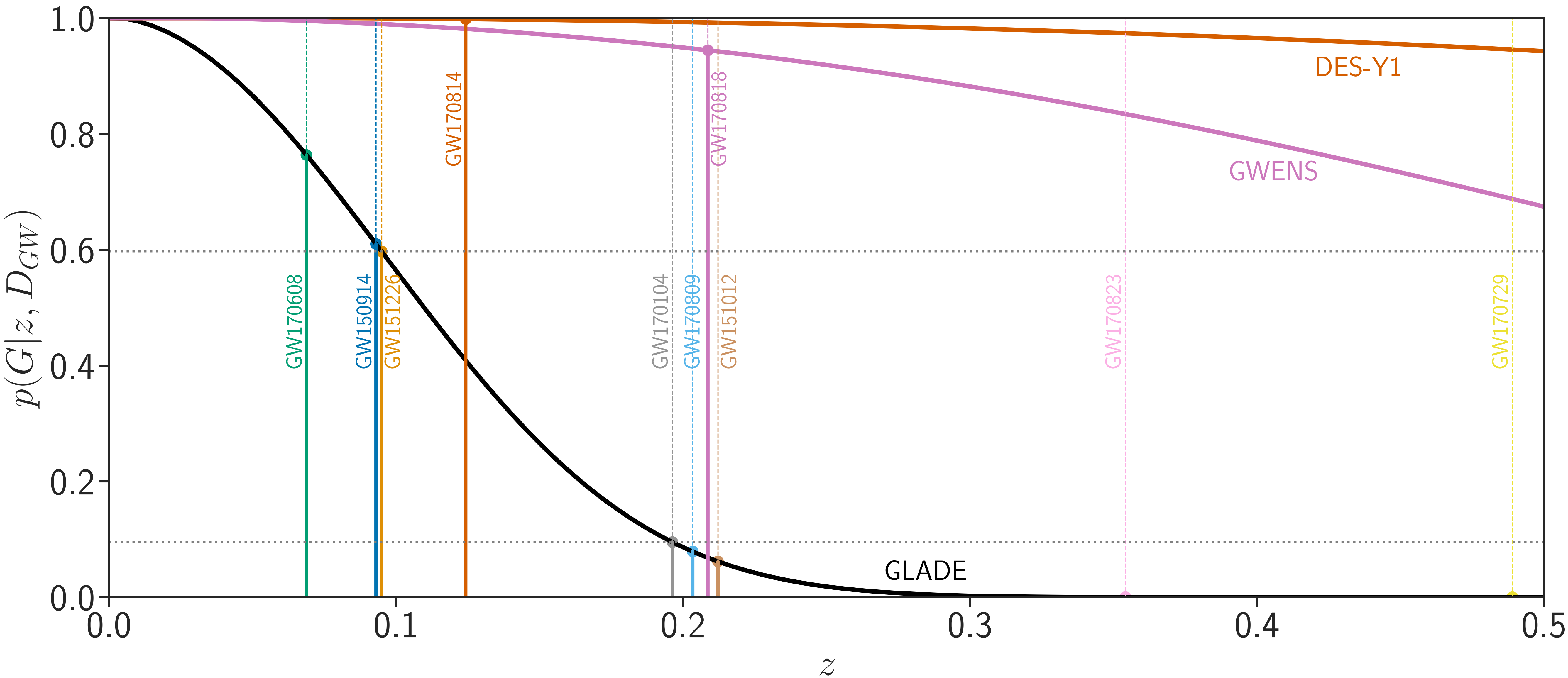
GWTC-1 Analysis





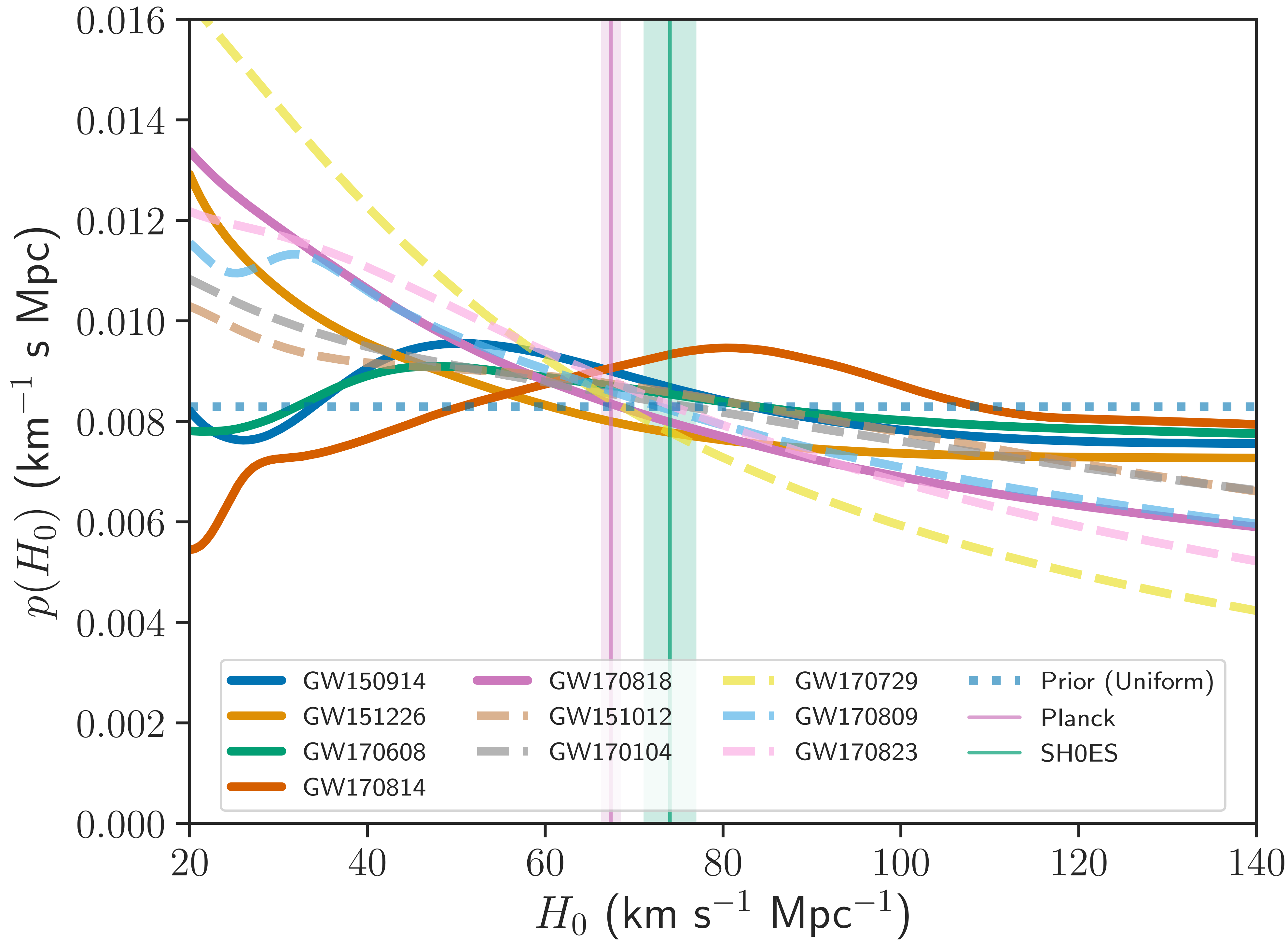
GWTC-1

Probability that the host galaxy is in the galaxy catalog



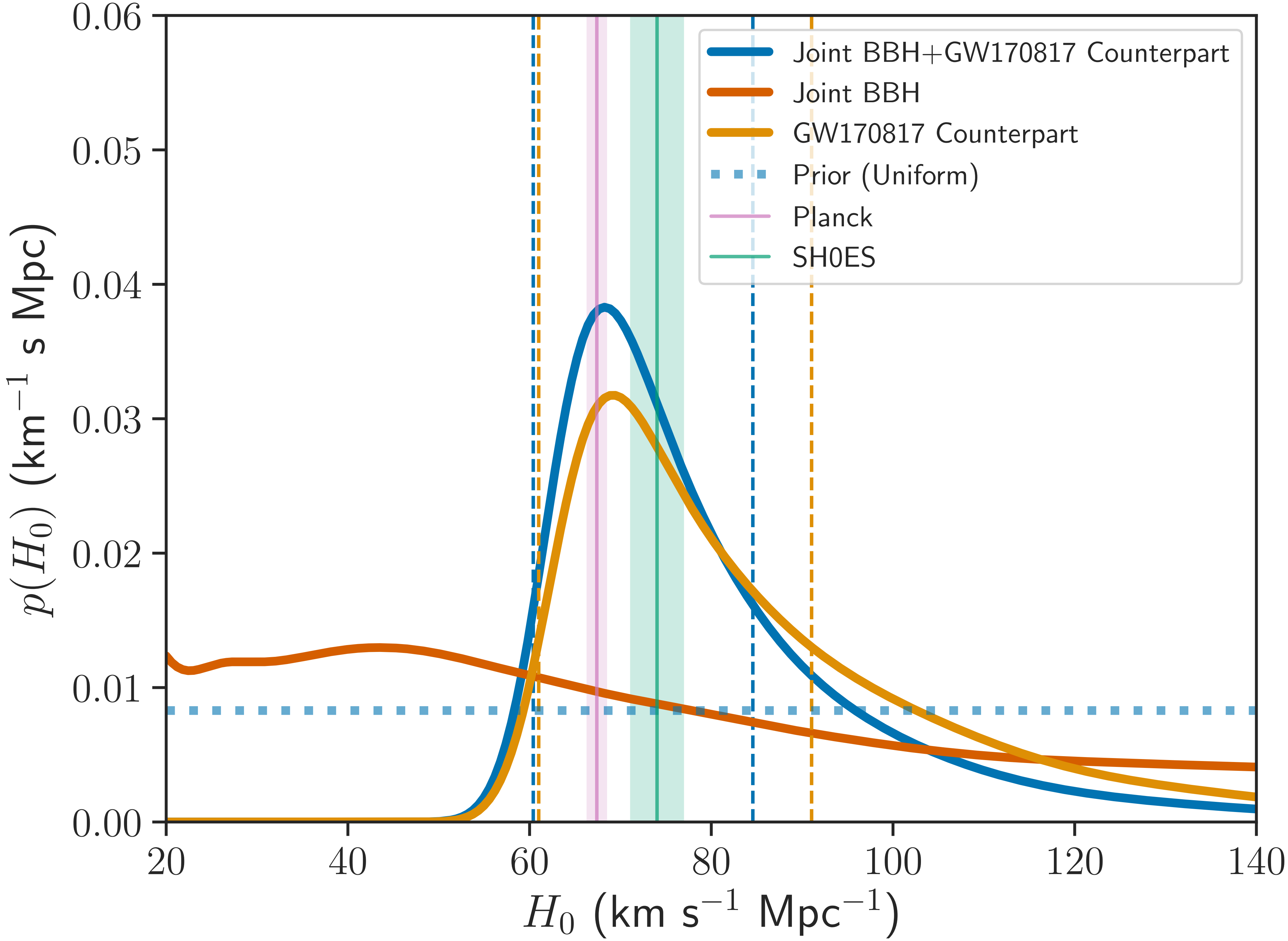
LVC+ 2019 arXiv:1908.06060

O1+O2 Measurement



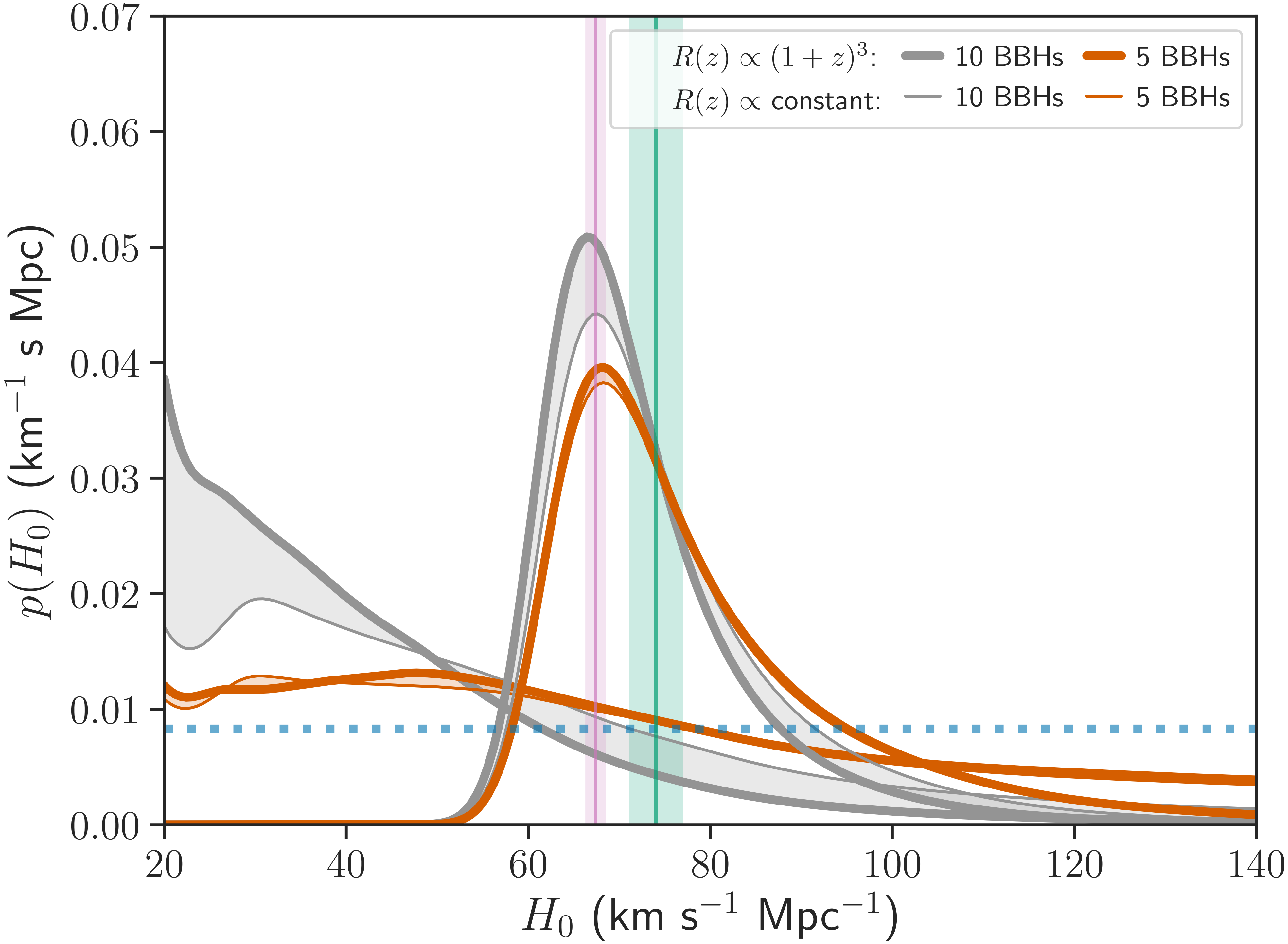
LVC+ 2019 arXiv:1908.06060

O1+O2 Measurement



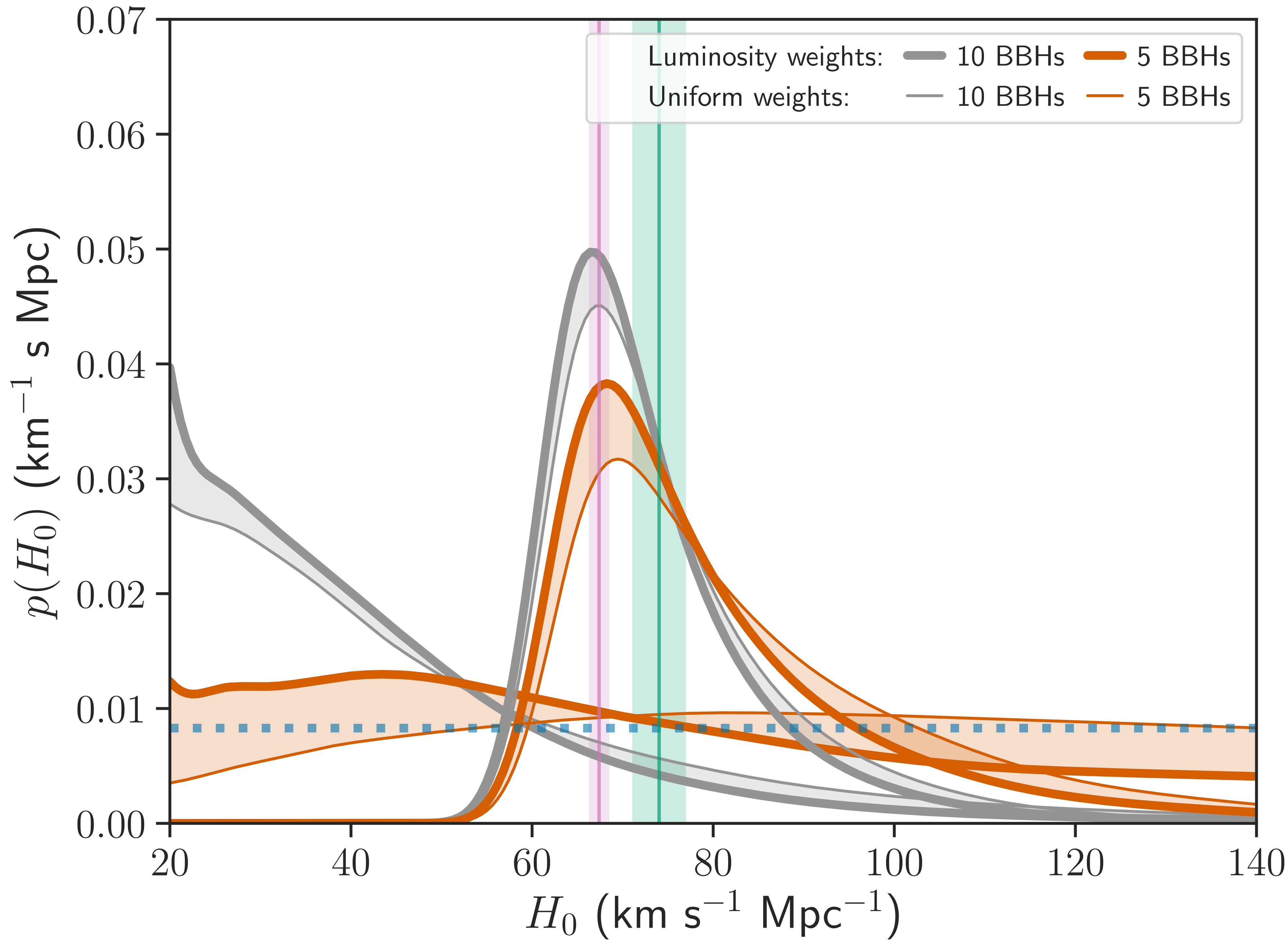
LVC+ 2019 arXiv:1908.06060

Caveats - Merger Rate Evolution



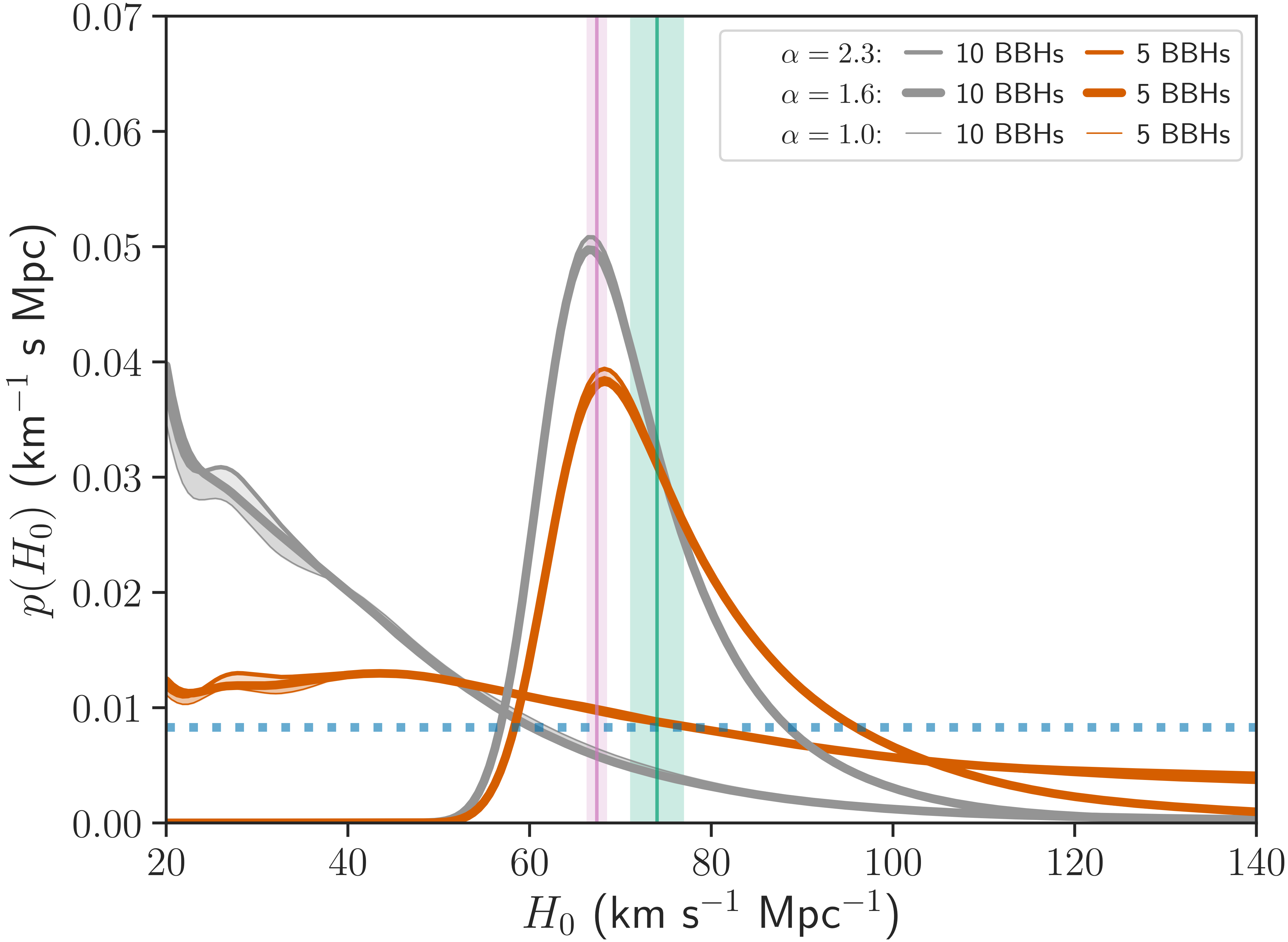
LVC+ 2019 arXiv:1908.06060

Caveats - Luminosity Weights



LVC+ 2019 arXiv:1908.06060

Caveats - Unknown Population



LVC+ 2019 arXiv:1908.06060

Conclusion

- GW standard sirens provide an independent measurement of cosmological parameters.
- GW+EM counterparts provide the tightest constrains.
- Statistical method uncertainty due to galaxy catalog incompleteness, photometric redshift uncertainties and large number of galaxies.
- More work needed to be done for the BBH statistical constrains: Incompleteness, large number of galaxies, etc.
- Statistical method might be the only way to constrain cosmology using binary black holes.

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Questions?